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New Formulas for HED, HMD, VED, and VMD Subsurface-to-Subsurface Propagation

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Preface

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New formulas for the electric and magnetic fields produced by the four elementary dipole antennas have been developed for the subsurface-to-subsurface, subsurface-to-surface, surface-to-subsurface, and surface-to-surface propagation cases. These formulas are of rather simple, but useful, form and are completely general (i.e., the air can easily be replaced by the sea bottom). They are valid at any frequency and at any range beyond a certain minimum distance for the flat-earth case. The main restrictions on these formulas are ~~(1)~~ that the square over

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of the index of refraction is $\geq$10 and ~~(2)~~ that the horizontal separation is $\geq$3 times the sum of the depths of burial of the transmitting and receiving point sources.

With these new formulas, computer evaluation can be reduced to fractions of a minute, compared with hours for the complete numerical evaluation of the exact Sommerfeld integrals.

There also will be an interference pattern set up under certain close-range conditions because the three waves (direct, modified mirror image, and lateral) may interfere, either constructively or destructively, with each other.

TABLE OF CONTENTS

LIST OF TABLES

GLOSSARY OF SYMBOLS

D	$(\rho^2 + h^2)^{1/2}$ (meters)
E_ρ	Horizontal electric-field component in the ρ direction (volts/meter)
E_ϕ	Horizontal electric-field component in the ϕ direction (volts/meter)
E_z	Vertical electric-field component (volts/meter)
F	$F(\omega_0)$, Sommerfeld ground-wave attenuation factor
h	Depth ($h \geq 0$) of transmitting antenna with respect to the earth's surface (meters)
H_ρ	Horizontal magnetic-field component in the ρ direction (amperes/meter)
H_ϕ	Horizontal magnetic-field component in the ϕ direction (amperes/meter)
H_z	Vertical magnetic-field component (amperes/meter)
HED	Horizontal electric dipole
HMD	Horizontal magnetic dipole
I	Current (amperes)
I_0	Modified Bessel function of the first kind and order zero
I_1	Modified Bessel function of the first kind and order one
$J_0(\lambda\rho)$	Bessel function of the first kind, order zero, with argument $\lambda\rho$
K_0	Modified Bessel function of the second kind and order zero
K_1	Modified Bessel function of the second kind and order one
m	Magnetic-dipole moment (ampere-meters^2)
n	γ_1/γ_0, index of refraction
N	$I_0\left\{\frac{\gamma_1}{2}[R_1 - (z + h)]\right\} K_0\left\{\frac{\gamma_1}{2}[R_1 + (z + h)]\right\}$ = Foster integral
p	Electric-current moment (amperes-meters)
P_0	$\exp(-\gamma_1 R_0)/R_0$ = Sommerfeld integral (meters^{-1})

GLOSSARY OF SYMBOLS (Cont'd)

P_1	$\exp(-\gamma_1 R_1)/R_1$ = Sommerfeld integral (meters^{-1})
R	$(\rho^2 + z^2)^{1/2}$ (meters)
R_0	$[\rho^2 + (z - h)^2]^{1/2}$ (meters)
R_1	$[\rho^2 + (z + h)^2]^{1/2}$ (meters)
t	Time (seconds)
T	$16 I_1 K_1 + \gamma^2 \rho^2 (I_1 K_1 - I_0 K_0) + 4\gamma\rho (I_1 K_0 - I_0 K_1)$
u_0	$(\lambda^2 + \gamma_0^2)^{1/2}$ (meters^{-1}) (air)
u_1	$(\lambda^2 + \gamma_1^2)^{1/2}$ (meters^{-1}) (earth)
VED	Vertical electric dipole
VMD	Vertical magnetic dipole
W	$3 I_1 K_1 - (\gamma\rho/2)(I_0 K_1 - I_1 K_0)$
ω_0	Sommerfeld numerical distance
z	Depth ($z \geq 0$) of receiving antenna with respect to earth's surface (meters)
γ_0	$(-\omega^2 \mu_0 \varepsilon_0)^{1/2}$, upper half-space (free-space) propagation constant (meters^{-1})
γ_1	$(i\omega\mu_1\sigma_1 - \omega^2 \mu_1 \varepsilon_1)^{1/2}$, lower half-space (earth) propagation constant (meters^{-1})
δ	$\left(\frac{2}{\omega\mu_0\sigma_1}\right)^{1/2} \left[\left(\frac{\omega^2\varepsilon_1^2}{\sigma_1^2} + 1\right)^{1/2} - \frac{\omega\varepsilon_1}{\sigma_1}\right]^{-1/2}$, skin depth in the lower half-space (earth) (meters)
ε_0	$\approx 10^{-9}/36\pi$ farads/meter, permittivity of free space
ε_1	Permittivity of lower half-space (earth) (farads/meter)
λ	Dummy integration variable in the basic Sommerfeld integrals (meters^{-1})
ρ	$(x^2 + y^2)^{1/2}$ radial distance in a cylindrical coordinate system (meters)
σ_1	Conductivity of the lower half-space (earth) (Siemens/meter)

GLOSSARY OF SYMBOLS (Cont'd)

ϕ	$\tan^{-1}(y/x)$, azimuth angle in a cylindrical coordinate system
$\mu \approx \mu_0$	$= 4\pi \times 10^{-7}$ henries/meter, permeability of free space
ψ	$\tan^{-1}[(z - h)/\rho]$, elevation angle
ψ_1	$\tan^{-1}[(z + h)/\rho]$, elevation angle
ω	$2\pi f$ radians/second, angular frequency

NEW FORMULAS FOR HED, HMD, VED, AND VMD SUBSURFACE-TO-SUBSURFACE PROPAGATION

INTRODUCTION

In two recent papers, Wu and King[1,2] have derived new simple formulas for the electric-field components generated by a horizontal electric dipole (HED) in a half-space of water or earth near its boundary with air. They claim that their formulas are valid for $\rho^2 \gg (z + h)^2$ and $|n^2| \gg 1$, where n $(= \gamma_1/\gamma_0)$ is the index of refraction. On examining their results, the author of this report has discovered that they could have been obtained almost by inspection from the previously derived results of Wait,[3] Weaver,[4] Bannister,[5] and Bannister and Hart[6] (most of which are summarized in Kraichman[7]).

In the past, many investigators erroneously have believed that the field-strength equations tabulated in chapter 3 of Kraichman are only valid when the conduction currents in the water or earth are much greater than the displacement currents (i.e., $\sigma_1 \gg \omega\epsilon_1$). Indeed, as long as $|n^2| \gg 1$, the displacement currents can be included simply by replacing σ_1 with $\sigma_1 + i\omega\epsilon_1$ in the field-strength equations. Thus, Kraichman's tabulated results are considerably more general than they are stated to be.

It is the purpose of this report to present new formulas for HED, horizontal magnetic dipole (HMD), vertical electric dipole (VED), and vertical magnetic dipole (VMD) subsurface-to-subsurface propagation. These formulas have been obtained completely from previously derived results. The main restrictions on their use are (1) the square of the index of refraction is $\geq$10 and (2) the horizontal separation is greater than or equal to three times the sum of the depths of burial of the transmitting and receiving point sources. An additional restriction must also be applied to the lateral-wave components. The quantity $|\gamma_1\rho^2/(z + h)|$ must be greater than or equal to $4c_1$, where c_1 = 3, 6, 9, 15, or 25, depending on the particular field-strength component. This restriction also applies to Wu-and-King's results[1,2] and to those tabulated in tables 3.7 and 3.16 of Kraichman.[7] These new formulas also avoid the use of the unphysical distance $z + h + \rho$ employed by Wu and King.[1,2]

In this report, the four dipole antennas (VED, VMD, HED, and HMD) are situated at depth h $(h \geq 0)$ with respect to a cylindrical coordinate system (ρ,ϕ,z) and are assumed to carry a constant current, I. The axes of the VED and HED (of dipole moment p) are oriented in the z and x directions, respectively, and the axes of the VMD and HMD (of dipole moment m) are oriented in the z and y directions, respectively. The earth or water occupies the lower half-space $(z > 0)$ while the air occupies the upper half-space $(z < 0)$. The magnetic permeability of the earth is assumed to equal μ_0, the permeability of free space. Meter-kilogram-second (MKS) units are employed and a suppressed time factor of $\exp(i\omega t)$ is assumed.

WU-AND-KING'S METHOD

In their first article,[1] Wu and King developed a new simple and very accurate formula for the radial electric field (E_ρ) of a HED in a dissipative or dielectric half-space near its boundary with air. They examined in detail the interference patterns generated by the direct and lateral waves that originate at the dipole for three values of ε_1, numerous values of σ_1, and a wide range of frequencies. They confirmed the accuracy of the new formula by comparison with numerically evaluated Sommerfeld integral results.

In their second article,[2] Wu and King developed new simple formulas for the transverse (E_ϕ) and vertical (E_z) electric-field components generated by a buried HED source. They then compared all three electric-field components with numerical integration results for the case where $\sigma_1 = 3.5$ S/m, $\varepsilon_1 = 45\varepsilon_0$, and f = 600 MHz (see figure 1 of Wu and King[2]). The agreement between the simple-formula and numerical-integration results was excellent for the radial component when $|\gamma_1\rho| > 2.8$ and $\rho > 2(z + h)$. However, substantial agreement between the simple-formula and numerical-integration transverse and vertical components was not achieved until $|\gamma_1\rho| > 11.5$ and $\rho > 8(z + h)$. Furthermore, the simple formulas predicted a dip in the transverse component and no dip in the vertical component near $|\gamma_1\rho| \sim 8$, while the numerical-integration results predicted the opposite.

Because the radial-component simple formula predicts the interference patterns very accurately and the transverse- and vertical-component simple formulas do not, it is apparent that Wu and King have made some errors in their transverse- and vertical-component derivations. A prime suspect is the unphysical distance term, $z + h + \rho$, which appears in the E_ϕ and E_z formulas but does not appear in the E_ρ formula. Wu and King could also have made a sign error so that the direct and lateral waves are adding instead of subtracting, or vice versa.

The procedure employed by Wu and King[1,2] can best be shown by example. When both the transmitting and receiving dipoles are located below the earth's surface (h and z $\geq$ 0), the HED Π_x vector may be expressed as (Wait[3])

$$\Pi_x = \frac{p}{4\pi(\sigma_1 + i\omega\varepsilon_1)}[P_0 - P_1 + I] \ , \tag{1}$$

where

$$P_0 = \frac{e^{-\gamma_1 R_0}}{R_0} \tag{2}$$

is the direct-wave contribution and

$$P_1 = \frac{e^{-\gamma_1 R_1}}{R_1} \tag{3}$$

is the mirror-image contribution. The remaining term is

$$I = 2\int_0^{\infty} \frac{e^{-u_1(z+h)}}{u_1 + u_0} J_0(\lambda\rho)\lambda d\lambda$$

$$= \frac{2}{(\gamma_1^2 - \gamma_0^2)}\int_0^{\infty} (u_1 - u_0)e^{-u_1(z+h)} J_0(\lambda\rho)\lambda d\lambda \ , \tag{4}$$

where

$R_0^2 = \rho^2 + (z - h)^2,$

$R_1^2 = \rho^2 + (z + h)^2,$

$u_0^2 = \lambda^2 + \gamma_0^2,$

$u_0^2 = \lambda^2 + \gamma_1^2,$

$u_1^2 = -\omega^2\mu_0\varepsilon_0$, and

$\gamma_1^2 = i\omega\mu_0(\sigma_1 + i\omega\varepsilon_1).$

For $|n^2| >> 1$ and $\rho^2 >> (z + h)^2$, Wu-and-King's procedure is to set R_0 and R_1 equal to ρ everywhere except in the exponents and let

$$e^{-u_1(z+h)} \sim e^{-\gamma_1(z+h)} \tag{5}$$

in equation (4). Therefore,

$$P_0 \sim \frac{e^{-\gamma_1 R_0}}{\rho} \tag{6}$$

$$P_1 \sim \frac{e^{-\gamma_1 R_1}}{\rho} \tag{7}$$

and

$$I \sim \frac{2e^{-\gamma_1(z+h)}}{(\gamma_1^2 - \gamma_0^2)}\int_0^{\infty} (u_1 - u_0)J_0(\lambda\rho)\lambda d\lambda \ . \tag{8}$$

This integral can be readily evaluated (Wait,[3] Erdélyi[8]) to yield

$$I \sim -\frac{2e^{-\gamma_1(z+h)}}{(\gamma_1^2 - \gamma_0^2)\rho^3}\left[(1 + \gamma_1\rho)e^{-\gamma_1\rho} - (1 + \gamma_0\rho)e^{-\gamma_0\rho}\right] . \tag{9}$$

Thus, by following the procedure of Wu and King,[1,2] the final expression for Π_x is (for $|n^2| >> 1$ and $\rho^2 >> (z + h)^2$)

$$\Pi_x \sim \frac{p}{4\pi(\sigma_1 + i\omega\epsilon_1)}\left\{\frac{e^{-\gamma_1 R_0}}{\rho} - \frac{e^{-\gamma_1 R_1}}{\rho} - \frac{2}{(\gamma_1^2 - \gamma_0^2)\rho^3}\left[(1 + \gamma_1\rho)e^{-\gamma_1(z+h+\rho)} - (1 + \gamma_0\rho)e^{-\gamma_0\rho}e^{-\gamma_1(z+h)}\right]\right\} . \tag{10}$$

Note that Π_x has four components: (1) a direct-wave component, (2) a mirror-image component, (3) a lateral-wave component, and (4) a false component that depends on the unphysical distance $z + h + \rho$.

BANNISTER'S METHOD

As we shall soon see, the unphysical distance $z + h + \rho$ can be avoided. When the measurement distance is much less than a free-space wavelength, equation (1) reduces to

$$\Pi_x \sim \frac{p}{4\pi(\sigma_1 + i\omega\epsilon_1)}\left[P_0 - P_1 + \frac{2}{(\gamma_1^2 - \gamma_0^2)}\int_0^\infty (u_1 - \lambda)e^{-u_1(z+h)} J_0(\lambda\rho)\lambda d\lambda\right] . \tag{11}$$

Wait[3] has shown that this equation is equivalent to

$$\Pi_x \sim \frac{p}{4\pi(\sigma_1 + i\omega\epsilon_1)}\left[P_0 - P_1 + \frac{2}{(\gamma_1^2 - \gamma_0^2)}\left(\frac{\partial^2 P_1}{\partial z^2} - \frac{\partial^3 N}{\partial z^3} + \gamma_1^2\frac{\partial N}{\partial z}\right)\right] , \tag{12}$$

where

$$N = I_0\left\{\frac{\gamma_1}{2}[R_1 - (z + h)]\right\}K_0\left\{\frac{\gamma_1}{2}[R_1 + (z + h)]\right\} . \tag{13}$$

Wait[3] has also shown that, when $|\gamma_1\rho| >> 1$ and $\rho >> (z + h)$,

$$N \sim \frac{e^{-\gamma_1(z+h)}}{\gamma_1\rho} . \tag{14}$$

Quoting Wait,[3] "The manner in which the exponential factor $\exp[-\gamma_1(z + h)]$ occurs is rather interesting. It is only in the integral N that this factor emerges."

Employing equation (14) and taking the indicated derivatives in equation (12) results in

$$\Pi_x \sim \frac{p}{4\pi(\sigma_1 + i\omega\epsilon_1)}\left\{\frac{e^{-\gamma_1 R_0}}{R_0} + \frac{2e^{-\gamma_1(z+h)}}{(\gamma_1^2 - \gamma_0^2)\rho^3} - \frac{e^{-\gamma_1 R_1}}{R_1}\right.$$
$$\left. - \frac{2e^{-\gamma_1 R_1}}{(\gamma_1^2 - \gamma_0^2)R_1^3}\left[(1 - 3\sin^2\psi_1)(1 + \gamma_1 R_1) - \gamma_1^2 R_1^2 \sin^2\psi_1\right]\right\}, \tag{15}$$

where $\sin \psi_1 = (z + h)/R_1$.

For $\rho^2 >> (z + h)^2$, we can set R_0 and R_1 equal to ρ everywhere except in the exponents. Thus,

$$\Pi_x \sim \frac{p}{4\pi(\sigma_1 + i\omega\epsilon_1)}\left\{\frac{e^{-\gamma_1 R_0}}{\rho} + \frac{2e^{-\gamma_1(z+h)}}{(\gamma_1^2 - \gamma_0^2)\rho^3}\right.$$
$$\left. - \frac{e^{-\gamma_1 R_1}}{\rho}\left[1 + \frac{2}{(\gamma_1^2 - \gamma_0^2)\rho^2}(1 + \gamma_1\rho)\right]\right\}. \tag{16}$$

Here, we see that Π_x has only three components: (1) a direct-wave component, (2) a modified mirror-image component, and (3) a lateral-wave component. There is no false component that depends on the unphysical distance $z + h + \rho$.

At first glance, this procedure appears to be considerably more complicated than the procedure employed by Wu and King. Luckily, however, the general quasi-static range field components have already been derived for the four elementary dipoles (Wait,[3] Weaver,[4] Bannister,[5] Bannister and Hart.[6] Wait and Campbell,[9,10] and Sinya and Bhattacharya[11]) as have the quasi-near, near-field, and farfield range lateral-wave expressions (tables 3.2, 3.7, and 3.16 of Kraichman[7]). Although displacement currents were ignored in most of these analyses, they can be included simply by replacing σ_1 by $\sigma_1 + i\omega\epsilon_1$ (as long as $|n^2| >> 1$). For convenience sake, the direct and modified mirror-image contribution to each dipole field-strength component is listed in the appendix. For some components, these expressions are of very simple form (H_ϕ^{VE}, equation (A-15)), while for other components, these expressions are quite complicated (H_z^{VM}, equation (A-18)).

Thus, the hardest part of the problem has already been solved. We can now use these previously derived results to obtain adequate formulas for the fields produced by submerged dipole sources subject to the conditions $|n^2| >> 1$ and $\rho^2 >> (z + h)^2$.

The derivation procedure that we will follow is (1) take the previously derived direct and modified mirror-image results (see appendix) and let ρ be $\geq 3(z + h)$, remembering not to replace R_0 and R_1 by ρ in the exponents, and (2) for the lateral-wave expressions, let

$$f(\rho, z + h) = f(\rho, 0)e^{-\gamma_1(z+h)}, \tag{17}$$

where 0 refers to an infinitesimal distance below the surface of the earth or water.

The quasi-static range ($|\gamma_0 \rho| << 1$) lateral-wave functions $f(\rho,0)$ can be obtained from Bannister[5] or table 3.8 of Kraichman[7] (with σ_1 replaced by $\sigma_1 + i\omega\varepsilon_1$). For convenience sake, the lateral-wave functions $f(\rho,0) \exp[-\gamma_1(z + h)]$ are presented in table 1.* Note that, for some of the field-strength components, these expressions are identical to the quasi-near range ($|\gamma_0\rho| << 1 << |\gamma_1\rho|$) results (see table 3.16 of Kraichman[7]). Also, note that some of the signs are different than those of Bannister[5] and Kraichman.[7] This is because, in this report, we have inverted the coordinate system so that z and h are positive depths.

Approximately half of the field-component formulas listed in table 1 involve products of modified Bessel functions of argument $\gamma_1\rho/2$. Numerical values for these functions have been provided by Bannister.[5] When $|\gamma_1\rho| \geq 4$, the function $\gamma_1\rho I_1 K_1 \sim 1$, while when $|\gamma_1\rho| \geq 6$, the function $\gamma_1\rho W \sim 2$. Furthermore, when $|\gamma_1\rho| \geq 10$, the function $\gamma_1\rho T/2 \sim 3$.

As an example of our derivation procedure, consider the HED radial electric field-strength component. The quasi-static range lateral-wave E_ρ component can be obtained from table 1 or from equation (67) of Wait.[3] It is equal to

$$E_\rho^{HE} \sim \frac{p \cos \phi}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^3} e^{-\gamma_1(z+h)} . \tag{18}$$

The nearfield range lateral-wave E_ρ component can be obtained from table 3.7 of Kraichman[7] (with σ_1 replaced by $\sigma_1 + i\omega\varepsilon_1$), or from equations (23) and (32) of Wait.[3] Therefore,

$$E_\rho^{HE} \sim \frac{p \cos \phi e^{-\gamma_1(z+h)} e^{-\gamma_0\rho}}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^3} (1 + \gamma_0\rho + \gamma_0^2\rho^2) . \tag{19}$$

The farfield range lateral-wave E_ρ component can be obtained from table 3.2 of Kraichman[7] (with σ_1 replaced by $\sigma_1 + i\omega\varepsilon_1$), or from equations (13) and (32) of Wait.[3] Thus,

$$E_\rho^{HE} \sim \frac{p \cos \phi e^{-\gamma_1(z+h)} e^{-\gamma_0\rho}}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^3} (\gamma_0^2\rho^2 F) , \tag{20}$$

where

$$F = F(w_0) = 1 - i(\pi w_0)^{1/2} e^{-w_0} \operatorname{erfc}(i w_0^{1/2}) \tag{21}$$

is the Sommerfeld surface-wave attenuation function and

*Tables have been placed together at the end of this report.

$$w_0 = -\frac{\gamma_0\rho}{2n^2} \tag{22}$$

is the Sommerfeld numerical distance. For small numerical distances $F(w_0) \sim 1$, while for large numerical distances $F(w_0) \sim -1/(2w_0)$.

When $|n^2| >> 1$, the range of validity of equations (18) and (19) overlap when $|\gamma_0\rho| << 1$. Similarly, when $|w_0| << 1$ and $|\gamma_0\rho| >> 1$, the range of validity of equations (19) and (20) overlap. Therefore, we can simply combine equations (18), (19), and (20) to obtain an expression for the E_ρ lateral-wave component valid from the quasi-static to the farfield range. Therefore, for $|n^2| >> 1$ and $\rho^2 >> (z + h)^2$,

$$E_\rho^{HE} \sim \frac{p \cos \phi e^{-\gamma_1(z+h)} e^{-\gamma_0\rho}}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^3} (1 + \gamma_0\rho + \gamma_0^2\rho^2F) . \tag{23}$$

The direct and modified mirror-image contribution to each dipole field-strength component is listed in the appendix. These expressions are valid for $|n^2| >> 1$. When $\rho \geq 3(z + h)$, equation (A-1) reduces to

$$E_\rho^{HE} \sim \frac{p \cos \phi}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^3}\Bigg\{(1 + \gamma_1\rho)e^{-\gamma_1 R_0} - (3 + 3\gamma_1\rho + \gamma_1^2\rho^2)\left[\frac{(z - h)^2}{2\rho^2}e^{-\gamma_1 R_0} + \frac{(z + h)^2}{2\rho^2}e^{-\gamma_1 R_1}\right]\Bigg\} . \tag{24}$$

We can now combine equations (23) and (24) and obtain an expression for the HED E_ρ component valid at almost any range from the source subject to the conditions that $|n^2| >> 1$ and $\rho \geq 3(z + h)$. The final expression is

$$E_\rho^{HE} \sim \frac{p \cos \phi}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^3}\Bigg\{(1 + \gamma_0\rho + \gamma_0^2\rho^2F)e^{-\gamma_0\rho}e^{-\gamma_1(z+h)} + (1 + \gamma_1\rho)e^{-\gamma_1 R_0} - (3 + 3\gamma_1\rho + \gamma_1^2\rho^2)\left[\frac{(z - h)^2}{2\rho^2}e^{-\gamma_1 R_0} + \frac{(z + h)^2}{2\rho^2}e^{-\gamma_1 R_1}\right]\Bigg\} . \tag{25}$$

When $\rho^2 >> (z + h)^2$, the last two terms of equation (25) are negligible compared with the first two, resulting in

$$E_\rho^{HE} \sim \frac{p \cos \phi}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^3}\Bigg[(1 + \gamma_0\rho + \gamma_0^2\rho^2F)e^{-\gamma_0\rho}e^{-\gamma_1(z+h)} + (1 + \gamma_1\rho)e^{-\gamma_1 R_0}\Bigg] , \tag{26}$$

which is identical to Wu-and-King's result[1] for $|n^2| >> 1$ and $\rho^2 >> (z + h)^2$. As we mentioned previously, Wu and King have shown that this simple formula is in excellent agreement with the exact Sommerfeld integral numerical-integration results.

New formulas for the electric and magnetic fields produced by the four elementary dipole antennas are presented in tables 2 through 9 for the subsurface-to-subsurface, subsurface-to-surface, surface-to-subsurface, and surface-to-surface propagation cases. All of these formulas have been obtained from previously derived results according to the procedure outlined above and are strictly valid for $|n^2| >> 1$ and $\rho^2 >> (z + h)^2$. (However, for most cases, the requirement that $|n^2| \geq 10$ and $\rho \geq 3(z + h)$ is sufficient.)

It should be noted that for many (but not all) cases, the range of validity of the formulas presented in tables 2 through 7 can be extended down to $\rho \sim (z + h)$ if the direct and modified mirror-image terms in these equations are replaced with the equations listed in the appendix. For example, the HED E_ρ expression (equation (25)) would be replaced by

$$\begin{aligned} E_\rho^{HE} \sim \frac{p \cos \phi}{4\pi(\sigma_1 + i\omega\varepsilon_1)} \Bigg\{ & \frac{2}{\rho^3}(1 + \gamma_0\rho + \gamma_0^2\rho^2 F) e^{-\gamma_0\rho} e^{-\gamma_1(z+h)} \\ & + [(3 \cos^2 \psi_0 - 1)(1 + \gamma_1 R_0) - \gamma_1^2 R_0^2 \sin^2 \psi_0] \frac{e^{-\gamma_1 R_0}}{R_0^3} \\ & - (3 + 3\gamma_1 R_1 + \gamma_1^2 R_1^2) \sin^2 \psi_1 \frac{e^{-\gamma_1 R_1}}{R_1^3} \Bigg\}, \end{aligned} \tag{27}$$

where $\sin \psi_0 = (z - h)/R_0$ and $\cos \psi_0 = \rho/R_0$.

For the subsurface-to-surface and surface-to-surface propagation cases (tables 4 and 8), the vertical electric-field (E_z) receiving antenna is assumed to be located an infinitesimal distance above the earth's surface. To obtain expressions for the vertical electric fields just below the surface, multiply the E_z equations in tables 4 and 8 by $1/n^2$.

COMPARISON OF BANNISTER AND WU-AND-KING RESULTS

In attempting to explain the major discrepancy between the HED E_ϕ and E_z simple-formula and numerical-integration results near $|\gamma_1\rho| \sim 8$ of their figure 1, Wu and King[2] stated that very small changes in frequency significantly alter the interference pattern so that close agreement in a small range near such a region cannot be expected. This statement is in direct opposition to the E_ρ results presented in their first article (Wu and King[1]), where substantial agreement between the simple-formula and numerical-integration results was achieved in the interference region when $|n^2| >> 1$ and $\rho \geq 5(z + h)$.

They also noted that, at greater distances where the lateral wave dominates, the E_ρ, E_ϕ, and E_z expressions were highly accurate. They certainly should be highly accurate at the greater distances because their lateral-wave formulas are essentially equivalent to Wait's results,[3] which have been successfully utilized for over 20 years.

The major value of Wu-and-King's work is in determining adequate field-strength expressions in the range where the lateral and direct waves interfere (either constructively or destructively). They have succeeded with the HED E_ρ component. However, they have made some errors in their derivation of the HED E_ϕ and E_z components.

The HED E_ϕ and E_z expressions derived in this report (table 2) are in very good agreement with the numerical-integration results presented in figure 1 of Wu and King[2] when $\rho \geq 3(z + h)$. They correctly predict a substantial dip in the E_z component (due tc interference between the direct, mirror-image, and lateral waves) near $|\gamma_1\rho| \sim 8$ and no dip in the E_ϕ component at this range (which is directly opposite to Wu-and-King's simple-formula results).

To see where Wu and King erred, we will compare their E_ϕ and E_z formulas with the expressions listed in table 2 for the situation where the Sommerfeld numerical distance is small (i.e., $F \sim 1$), $\rho \geq 5(z + h)$, and $|\gamma_1\rho| \geq 4$. For this situation, the E_ϕ and E_z expressions in table 2 reduce to

$$E_\phi^{HE} \sim \frac{p \sin \phi}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^3}\left[2(1 + \gamma_0\rho)e^{-\gamma_0\rho}e^{-\gamma_1(z+h)} - (1 + \gamma_1\rho)e^{-\gamma_1 R_1} + \frac{1}{2}(1 + \gamma_1\rho + \gamma_1^2\rho^2)\left(e^{-\gamma_1 R_0} - e^{-\gamma_1 R_1}\right)\right] \tag{28}$$

and

$$E_z^{HE} \sim -\frac{p \cos \phi}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^2}\left\{\frac{\gamma_1}{n^2}(1 + \gamma_0\rho)e^{-\gamma_0\rho}e^{-\gamma_1(z+h)} - \frac{1}{2\rho^2}(3 + 3\gamma_1\rho + \gamma_1^2\rho^2)\left[(z - h)e^{-\gamma_1 R_0} + (z + h)e^{-\gamma_1 R_1}\right]\right\}. \tag{29}$$

When $F \sim 1$, $\rho \geq 5(z + h)$, and $|\gamma_1\rho| \geq 4$, Wu-and-King's[2] E_ϕ and E_z expressions reduce to

$$E_\phi^{HE} \sim \frac{p \sin \phi}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^3}\left[2(1 + \gamma_0\rho)e^{-\gamma_0\rho}e^{-\gamma_1(z+h)} - (2 + 2\gamma_1\rho + \gamma_1^2\rho^2)e^{-\gamma_1(z+h+\rho)} + (1 + \gamma_1\rho + \gamma_1^2\rho^2)e^{-\gamma_1 R_1} + \frac{1}{2}(1 + \gamma_1\rho + \gamma_1^2\rho^2)\left(e^{-\gamma_1 R_0} - e^{-\gamma_1 R_1}\right)\right] \tag{30}$$

and

$$E_z^{HE} \sim \frac{p \cos \phi}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^2}\left\{\frac{\gamma_1}{n^2}(1 + \gamma_0\rho)e^{-\gamma_0\rho}e^{-\gamma_1(z+h)} + \frac{1}{2\rho^2}(3 + 3\gamma_1\rho + \gamma_1^2\rho^2)\left[(z - h)e^{-\gamma_1 R_0} + (z + h)e^{-\gamma_1 R_1}\right]\right\}. \tag{31}$$

A comparison of the two E_ϕ expressions (equations (28) and (30)) reveals that the difference between them is the unphysical distance $(z + h + \rho)$ term of Wu and King. If we replace $z + h + \rho$ by the physical distance R_1, Wu-and-King's formula reduces to

$$E_\phi^{HE} \sim \frac{p \sin \phi}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^3}\left[2(1 + \gamma_0\rho)e^{-\gamma_0\rho}e^{-\gamma_1(z+h)} - (1 + \gamma_1\rho)e^{-\gamma_1 R_1} + \frac{1}{2}\left(1 + \gamma_1\rho + \gamma_1^2\rho^2\right)\left(e^{-\gamma_1 R_0} - e^{-\gamma_1 R_1}\right)\right] , \tag{32}$$

which is identical to equation (28).

A comparison of the two E_z expressions (equations (29) and (31)) reveals that the reason that Wu-and-King's formula does not predict the dip in the interference region is because of a sign error. Their results indicate that the sum of the direct and mirror-image waves add to the lateral wave whereas, in reality, the sum subtracts from the lateral wave.

RANGE OF VALIDITY OF LATERAL-WAVE FORMULAS

As we have previously mentioned, the quasi-static range lateral-wave exponential attenuation-with-depth factor $\exp[-\gamma_1(z + h)]$ emerges only from the integral N, where

$$N = I_0\left\{\frac{\gamma_1}{2}[R_1 - (z + h)]\right\}K_0\left\{\frac{\gamma_1}{2}[R_1 + (z + h)]\right\} . \tag{13}$$

When $|\gamma_1\rho| >> 1$ and $\rho >> (z + h)$, Wait and Campbell[10] have shown that the modified Bessel functions may be replaced by only the first terms in their respective asymptotic expansions to obtain adequate HMD quasi-near range horizontal magnetic-field-component expressions. On the other hand, Sinha and Bhattacharya[11] have shown, for the VMD case, the first two terms of the modified Bessel function's asymptotic expansions must be employed. This indicates that the range of validity of the quasi-static range lateral-wave expressions will not be the same for all field components.

As an example, consider the quasi-static range HED E_ρ lateral-wave component, which can be expressed as

$$E_\rho^{LW} \sim - \frac{p \cos \phi}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho} \frac{\partial}{\partial\rho}\int_0^\infty e^{-u_1(z+h)} J_0(\lambda\rho)d\lambda . \tag{33}$$

When $|\gamma_1\rho| >> 1$ and $\rho >> (z + h)$, the usual procedure is to replace μ_1 in the exact integral expressions by γ_1, the propagation constant in the earth, resulting in

$$E_\rho^{LW} \sim -\frac{p\cos\phi e^{-\gamma_1(z+h)}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho}\frac{\partial}{\partial\rho}\int_0^\infty J_0(\lambda\rho)d\lambda \ . \tag{34}$$

Since this integral is equal to $1/\rho$ (Erdélyi[8]),

$$E_\rho^{LW} \sim \frac{p\cos\phi e^{-\gamma_1(z+h)}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^3} = f(\rho,0)e^{-\gamma_1(z+h)} \ . \tag{35}$$

So far, we do not know exactly what values $|\gamma_1\rho|$ and $\rho/(z + h)$ must have in order to utilize equation (35) or any of the other quasi-static range lateral-wave formulas presented in table 1.

As a first order approximation, we will let

$$u_1 = (\lambda^2 + \gamma_1^2)^{1/2} \sim \gamma_1 + \frac{\lambda^2}{2\gamma_1} \tag{36}$$

so that

$$e^{-u_1(z+h)} \sim e^{-\gamma_1(z+h)}e^{-\lambda^2(z+h)/2\gamma_1} \sim e^{-\gamma_1(z+h)}\left[1 - \frac{\lambda^2(z + h)}{2\gamma_1}\right] . \tag{37}$$

Inserting equation (37) into equation (33) results in

$$E_\rho^{LW} \sim -\frac{p\cos\phi e^{-\gamma_1(z+h)}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho}\frac{\partial}{\partial\rho}\left[\int_0^\infty J_0(\lambda\rho)d\lambda - \frac{(z + h)}{2\gamma_1}\int_0^\infty \lambda^2 J_0(\lambda\rho)d\lambda\right] . \tag{38}$$

Since the second integral is equal to $-1/\rho^3$ (Erdélyi[8]),

$$E_\rho^{LW} \sim \frac{p\cos\phi e^{-\gamma_1(z+h)}}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^3}\left[1 + \frac{3(z + h)}{2\gamma_1\rho^2}\right] . \tag{39}$$

It can easily be shown that the error incurred in neglecting the second term is less than 1 dB if the quantity

$$\left|(\gamma_1\rho)\left(\frac{\rho}{z + h}\right)\right| \geq 4c_1 \ , \tag{40}$$

where $c_1 = 3$ for the HED E_ρ component. That is, to a first order approximation, it is the product of $|\gamma_1\rho|$ times $\rho/(z + h)$ that must exceed a specified number to accurately utilize equation (35) or any of the other quasi-static range

lateral-wave formulas presented in table 1. For example, if $\rho = 5(z + h)$, the quantity $|\gamma_1\rho|$ must be ≥ 2.4 to use equation (35).

The most severe restriction will be for the VMD H_z component. Following the same procedure as in the derivation of the HED E_ρ component, we can express the VMD H_z component as

$$H_z^{VM} \sim -\frac{9me^{-\gamma_1(z+h)}}{2\pi(\gamma_1^2 - \gamma_0^2)\rho^5}\left[1 + \frac{25(z + h)}{2\gamma_1\rho^2}\right] . \tag{41}$$

Again, it can easily be shown that the error incurred in neglecting the second term is less than 1 dB if the quantity

$$\left|(\gamma_1\rho)\left(\frac{\rho}{z + h}\right)\right| \geq 4c_1 , \tag{40}$$

where $c_1 = 25$ for the VMD H_z component. For example, if $\rho = 5(z + h)$, the quantity $|\gamma_1\rho|$ must be ≥ 20 to employ the quasi-static range VMD H_z lateral-wave formula presented in table 1.

The values of c_1 and range where $f(\rho,z + h)$ can be replaced by $f(\rho,0)$ $\exp[-\gamma_1(z + h)]$ (i.e., the range where the quasi-static range lateral-wave formulas presented in table 1 can be used) are presented in table 10 for each field-strength component. Here, we see that for the HED and HMD E_ρ, E_z, and H_ϕ components and the VED E_ρ and H_ϕ components ($c_1 = 3$), the quantity $|\gamma_1\rho^2/(z + h)|$ must be ≥ 12, while for the HED H_z and VMD E_ϕ and H_ρ components ($c_1 = 15$), the quantity $|\gamma_1\rho^2/(z + h)|$ must be ≥ 60.

This restriction (equation (40)) also applies to Wu-and-King's results[1,2] and to the quasi-near and nearfield range subsurface-to-subsurface propagation equations tabulated in Kraichman.[7]

To a first order approximation, the range of validity of the equations listed in table 1 can be extended by multiplying the field-component expressions by the quantity

$$1 + \frac{c_1(z + h)}{2\gamma_1\rho^2} , \tag{42}$$

where the value of c_1 for each component is given in table 10. For example, the HED H_z component listed in table 1 is

$$H_z^{HE} \sim \frac{3p \sin \phi e^{-\gamma_1(z+h)}}{2\pi(\gamma_1^2 - \gamma_0^2)\rho^4} . \tag{43}$$

Since $c_1 = 15$ for this component (table 10), then

$$H_z^{HE} \sim \frac{3p \sin \phi e^{-\gamma_1(z+h)}}{2\pi(\gamma_1^2 - \gamma_0^2)\rho^4}\left[1 + \frac{15(z + h)}{2\gamma_1\rho^2}\right] . \tag{44}$$

ANALYTICAL CONFIRMATION OF FRASER-SMITH AND BUBENIK VMD H_z NULL

A few years ago, Fraser-Smith and Bubenik[12] numerically evaluated the exact Sommerfeld integrals and found a rather deep null in the VMD H_z component for the subsurface-to-surface propagation case (see figure 6 of Fraser-Smith and Bubenik[12]). For their particular situation, the frequency was 100 Hz, the VMD source depth of burial was 100 m, and the null occurred around $\rho \sim 250$ m. Since the skin depth, δ, in sea water at 100 Hz is ~25 m, $\rho/\delta \sim 10$ and $h/\delta \sim 4$. To our knowledge, this null has not been analytically confirmed. The subsurface-to-surface VMD H_z component is equal to (from table 5)

$$\begin{aligned} H_z^{VM} \sim -\frac{m}{2\pi(\gamma_1^2 - \gamma_0^2)\rho^5}\Bigg\{&(9 + 9\gamma_0\rho + 4\gamma_0^2\rho^2 + \gamma_0^3\rho^3)e^{-\gamma_0\rho}e^{-\gamma_1 h} \\ &- e^{-\gamma_1 D}\Bigg[(9 + 9\gamma_1\rho + 4\gamma_1^2\rho^2 + \gamma_1^3\rho^3) \\ &- \frac{h^2}{\rho^2}(90 + 90\gamma_1\rho + 39\gamma_1^2\rho^2 + 9\gamma_1^3\rho^3 + \gamma_1^4\rho^4)\Bigg]\Bigg\} , \end{aligned} \tag{45}$$

where $D^2 = \rho^2 + h^2$.

For f = 100 Hz and $\rho = 250$ m, $|\gamma_0\rho| << 1$ and the $\gamma_0\rho$ terms in the lateral-wave portion of equation (45) are negligible. Furthermore, since the quantity $|\gamma_1\rho^2/h| \sim 35$, which is <100 (see table 10), equation (42) must be employed. The resulting expression for H_z is

$$H_z^{VM} \sim -\frac{9me^{-\gamma_1 h}}{2\pi\gamma_1^2\rho^5} H_z' , \tag{46}$$

where

$$\begin{aligned} H_z' \sim \left(1 + \frac{25h}{2\gamma_1\rho^2}\right) - \Bigg\{&\frac{e^{-\gamma_1(D-h)}}{9}\Bigg[(9 + 9\gamma_1\rho + 4\gamma_1^2\rho^2 + \gamma_1^3\rho^3) \\ &- \frac{h^2}{\rho^2}(90 + 90\gamma_1\rho + 39\gamma_1^2\rho^2 + 9\gamma_1^3\rho^3 + \gamma_1^4\rho^4)\Bigg]\Bigg\} . \end{aligned} \tag{47}$$

For $\rho/\delta \sim 10$, the dominant terms will be the $\gamma_1^3\rho^3$ and $\gamma_1^4\rho^4$ terms. To a first order approximation, the $\gamma_1^3\rho^3$ terms will cancel and, since $\gamma_1^4\rho^4 = -4(\rho/\delta)^4$,

$$H_z' \sim 1 + \frac{25h}{2\gamma_1\rho^2} - \frac{4}{9}\left(\frac{h}{\rho}\right)^2\left(\frac{\rho}{\delta}\right)^4 e^{-(D-h)/\delta} e^{-i(D-h)/\delta} \quad . \tag{48}$$

This equation will be at a minimum near $(D - h)/\delta = 2\pi$, which corresponds to $\rho \sim 240$ m. The normalized VMD vertical magnetic field (H_z' from equation (47)) is plotted in figure 1 versus the horizontal distance, ρ. From this figure, we can see that a rather deep null (~20 dB drop in field strength compared to the asymptotic value) occurs at a range of ~240 m. This null is clearly due to the destructive interference between the direct and lateral waves.

CONCLUSIONS

New formulas for the electric and magnetic fields produced by the four elementary dipole antennas have been developed for the subsurface-to-subsurface propagation case. These formulas have been obtained completely from previously derived results. The main restrictions in their use are (1) the square of the index of refraction is ≥ 10 and (2) the horizontal separation is ≥ 3 times the sum of the depth of burial of the transmitting and receiving point sources. An additional restriction must also be applied to the lateral-wave components. The quantity $|\gamma_1\rho^2/(z + h)|$ must be $\geq 4c_1$, where c_1 = 3, 6, 9, 15, or 25, depending on the particular field-strength component. This restriction also applies to Wu-and-King's recently derived results[1,2] and to the subsurface-to-subsurface propagation equations tabulated in Kraichman.[7]

The range of validity of the subsurface-to-subsurface, subsurface-to-surface, and surface-to-subsurface equations tabulated in this report can be extended down to $\rho \sim (z + h)$ for many cases if the direct and modified mirror-image terms in these equations are replaced with the equations listed in the appendix. The extension of these results to even closer ranges will be the subject of a future report.

It should be noted that the two media can be inverted and the air replaced by the earth's crust (of conductivity σ_2 and dielectric constant ε_2). The same equations (tables 1 through 10) can be utilized, as long as $|n_2^2| = |\gamma_1^2/\gamma_2^2| \geq 10$ and $\rho \geq 3(z + h)$, simply by replacing $i\omega\varepsilon_0$ by $\sigma_2 + i\omega\varepsilon_2$.

An analytical confirmation of the Fraser-Smith and Bubenik VMD H_z null has also been accomplished. This null is clearly due to the destructive interference between the direct and lateral waves.

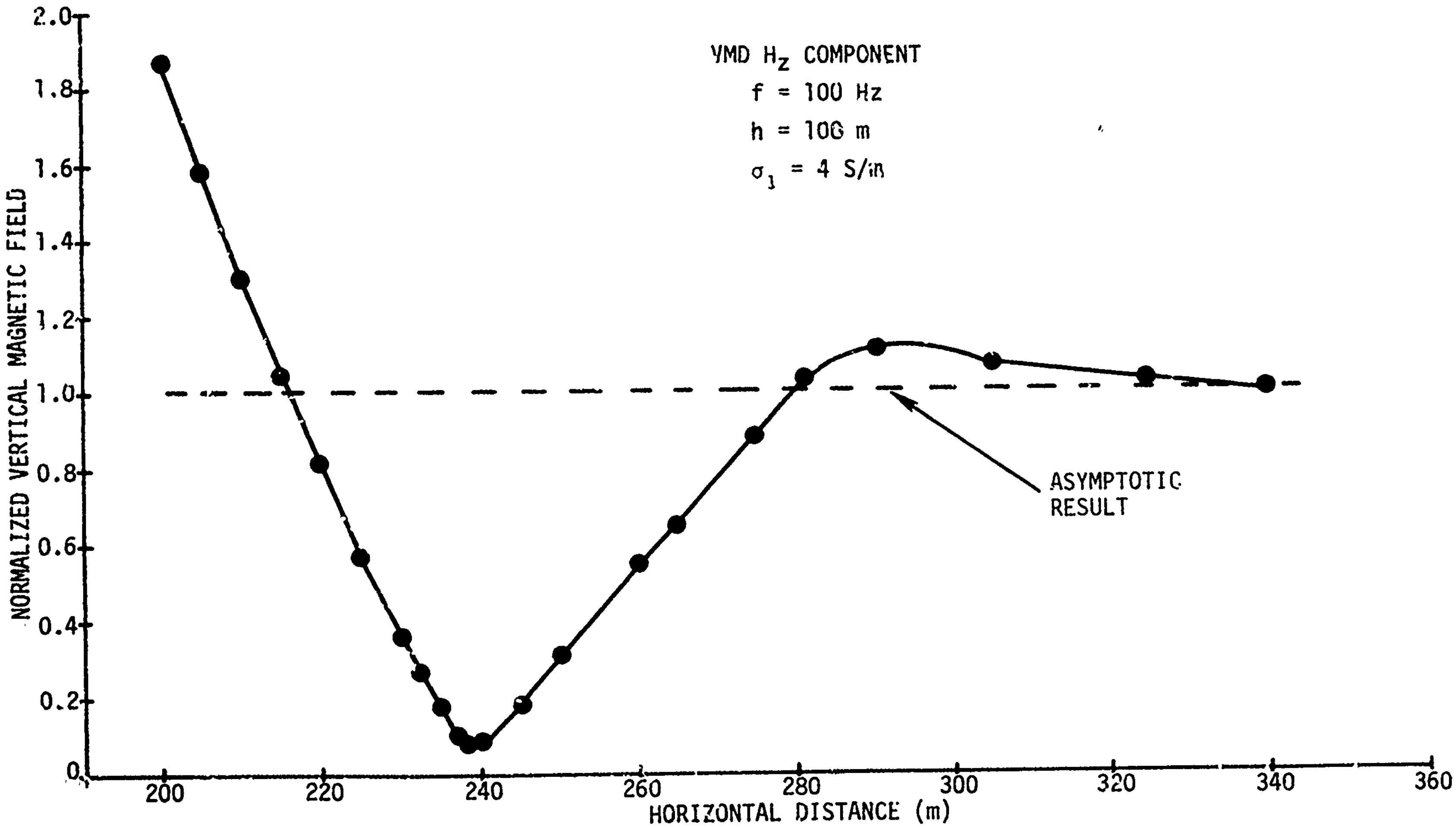

Figure 1. Normalized VMD Vertical Magnetic Field Versus Distance for $f = 100$ Hz, $h = 100$ m, and $\sigma_1 = 4$ S/m

Table 1. $f(\rho,0)e$
$|\gamma_0\rho| << 1$

Dipole Type	E_ρ	E_ϕ	E_z
VED	$\frac{\gamma\, pe^{-\gamma_1(z+h)}}{2\pi(\sigma_1 + i\omega\varepsilon_1)n^2\rho^2}(\gamma_1\rho I_1 K_1)$	0	$-\frac{pe^{-\gamma_1(z+h)}}{2\pi(\sigma_1 + i\omega\varepsilon_1)n^2\rho}$
VMD	0	$-\frac{3i\omega\mu_0 m}{2\pi(\gamma_1^2 - \gamma_0^2)\rho^4}e^{-\gamma_1(z+h)}$	0
HED	$\frac{p \cos\phi e^{-\gamma_1(z+h)}}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^3}$	$\frac{p \sin\phi e^{-\gamma_1(z+h)}}{\pi(\sigma_1 + i\omega\varepsilon_1)\rho^3}$	$-\frac{\gamma_1 p \cos\phi e^{-\gamma_1(z+}}{2\pi(\sigma_1 + i\omega\varepsilon_1)n^2\rho}$
HMD	$-\frac{i\omega\mu_0 m \cos\phi}{2\pi\gamma_1\rho^3}(\gamma_1\rho I_1 K_1) \times e^{-\gamma_1(z+h)}$	$-\frac{i\omega\mu_0 m \sin\phi}{2\pi\gamma_1\rho^3}(\gamma_1\rho W) \times e^{-\gamma_1(z+h)}$	$\frac{i\omega\mu_0 m \cos\phi}{2\pi n^2\rho^2}e^{-\gamma_1(z+}$

*Argument of modified Bessel functions is $\gamma_1\rho/2$.

... $f(\rho,0)e^{-\gamma_1(z+h)}$ Lateral Wave Formulas When
$|\gamma_0\rho| \ll 1$ $[|n^2| \geq 10,\ \rho^2 \gg (z+h)^2]$*

E_z	H_ρ	H_ϕ	H_z
$\frac{\ldots\gamma_1(z+h)}{\ldots i\omega\varepsilon_1)n^2\rho^3}$	0	$\frac{pe^{-\gamma_1(z+h)}}{2\pi n^2\rho^2}$	0
0	$\frac{me^{-\gamma_1(z+h)}}{2\pi\gamma_1\rho^4}\left(\frac{\gamma_1\rho T}{2}\right)$	0	$-\frac{9me^{-\gamma_1(z+h)}}{2\pi(\gamma_1^2-\gamma_0^2)\rho^5}$
$\frac{\ldots\phi e^{-\gamma_1(z+h)}}{\ldots i\omega\varepsilon_1)n^2\rho^2}(\gamma_1\rho I_1K_1)$	$-\frac{p\sin\phi e^{-\gamma_1(z+h)}}{2\pi\gamma_1\rho^3}(\gamma_1\rho W)$	$\frac{p\cos\phi e^{-\gamma_1(z+h)}}{2\pi\gamma_1\rho^3}(\gamma_1\rho I_1K_1)$	$\frac{3p\sin\phi e^{-\gamma_1(z+h)}}{2\pi(\gamma_1^2-\gamma_0^2)\rho^4}$
$\frac{\ldots\phi}{\ldots}e^{-\gamma_1(z+h)}$	$\frac{m\sin\phi}{\pi\rho^3}\left(1-\frac{6}{\gamma_1^2\rho^2}\right)e^{-\gamma_1(z+h)}$	$-\frac{m\cos\phi}{2\pi\rho^3}\left(1-\frac{3}{\gamma_1^2\rho^2}\right)e^{-\gamma_1(z+h)}$	$-\frac{m\sin\phi e^{-\gamma_1(z+h)}}{2\pi\gamma_1\rho^4}\left(\frac{\gamma_1\rho T}{2}\right)$

l 2

Table 2. Electric-Field Subsurface-to-Sub

Dipole Type	E_ρ	
VED	$\frac{p}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^2}\left\{\left(\frac{\gamma_1}{n^2}\right)(\gamma_1\rho I_1K_1 + \gamma_0\rho F)e^{-\gamma_0\rho}e^{-\gamma_1(z+h)}\right.$ $\left. - \frac{1}{2\rho^2}(3 + 3\gamma_1\rho + \gamma_1\rho^2)\left[(z + h)e^{-\gamma_1R_1} - (z - h)e^{-\gamma_1R_0}\right]\right\}$	
VMD	0	$- \frac{i\omega\mu_0 m}{2\pi(\gamma_1^2 - \gamma_0^2)\rho^4}\{(3 + 3$ $- [(3 + 3\gamma_1\rho + \gamma_1^2\rho^2) -$ $+ \frac{(\gamma_1^2 - \gamma^2)\rho^2}{2}(1 + \gamma_1\rho)$
HED	$\frac{p \cos \phi}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^3}\left\{(1 + \gamma_0\rho + \gamma_0^2\rho^2F)e^{-\gamma_0\rho}e^{-\gamma_1(z+h)}\right.$ $+ (1 + \gamma_1\rho)e^{-\gamma_1R_0} - (3 + 3\gamma_1\rho + \gamma_1^2\rho^2)$ $\left.\times \left[\frac{(z - h)^2}{2\rho^2}e^{-\gamma_1R_0} + \frac{(z + h)^2}{2\rho^2}e^{-\gamma_1R_1}\right]\right\}$	$\frac{p \sin \phi}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^3}\{[2 + \gamma$ $- [(1 + \gamma_1\rho) - \frac{(z + h)}{\rho^2}$ $+ \frac{1}{2}(1 + \gamma_1\rho + \gamma_1^2\rho^2)(e^{-}$
HMD	$- \frac{i\omega\mu_0 m \cos \phi}{2\pi\gamma_1\rho^3}\left\{(\gamma_1\rho I_1K_1 + \gamma_0\rho + \gamma_0^2\rho^2F)e^{-\gamma_0\rho}e^{-\gamma_1(z+h)}\right.$ $- \frac{\gamma_1(z + h)}{\gamma_1^2\rho^2}(3 + 3\gamma_1\rho + \gamma_1^2\rho^2)e^{-\gamma_1R_1}$ $\left. + \frac{(1 + \gamma_1\rho)}{2}\left[\gamma_1(z - h)e^{-\gamma_1R_0} - \gamma_1(z + h)e^{-\gamma_1R_1}\right]\right\}$	$- \frac{i\omega\mu_0 m \sin \phi}{2\pi\gamma_1\rho^3}\{[\gamma_1\rho W +$ $- \frac{\gamma_1(z + h)e^{-\gamma_1R_1}}{\gamma_1^2\rho^2}[(12$ $+ 6\gamma_1^2\rho^2 + \gamma_1^3\rho^3)] - \frac{(1}{}$

*Argument of modified Bessel function is $\gamma_1\rho/2$.

urface-to-Subsurface Propagation Formulas $[|n^2| \geq 10,\ \rho \geq 3(z+h)]$*

E_ϕ	E_z
0	$-\frac{p}{2\pi(\sigma_1+i\omega\epsilon_1)\rho^3}\Big[\left(\frac{1}{n^2}\right)(1+\gamma_0\rho+\gamma_0^2\rho^2F)e^{-\gamma_0\rho}e^{-\gamma_1(z+h)}$ $+\frac{1}{2}(1+\gamma_1\rho+\gamma_1^2\rho^2)\left(e^{-\gamma_1R_0}-e^{-\gamma_1R_1}\right)\Big]$
$\frac{\ \ m}{\ \ \gamma_0^2)\rho^4}\Big\{(3+3\gamma_0\rho+\gamma_0^2\rho^2)e^{-\gamma_0\rho}e^{-\gamma_1(z+h)}$ $\gamma_1\rho+\gamma_1^2\rho^2)-\frac{(z+h)^2}{\rho^2}(15+15\gamma_1\rho+6\gamma_1^2\rho^2+\gamma_1^3\rho^3)\Big]e^{-\gamma_1R_1}$ $)\rho^2\ (1+\gamma_1\rho)\left(e^{-\gamma_1R_0}-e^{-\gamma_1R_1}\right)\Big\}$	0
$\frac{\ \ \phi}{\ \ \epsilon_1)\rho^3}\Big\{[2+\gamma_0\rho(1+F)]e^{-\gamma_0\rho}e^{-\gamma_1(z+h)}$ $\rho)-\frac{(z+h)^2}{\rho^2}(3+3\gamma_1\rho+\gamma_1^2\rho^2)\Big]e^{-\gamma_1R_1}$ $\rho+\gamma_1^2\rho^2)\left(e^{-\gamma_1R_0}-e^{-\gamma_1R_1}\right)\Big\}$	$-\frac{p\cos\phi}{2\pi(\sigma_1+i\omega\epsilon_1)\rho^2}\Big\{\left(\frac{\gamma_1}{n^2}\right)(\gamma_1\rho I_1K_1+\gamma_0\rho F)e^{-\gamma_0\rho}e^{-\gamma_1(z+h)}$ $-\frac{1}{2\rho^2}(3+3\gamma_1\rho+\gamma_1^2\rho^2)\left[(z-h)e^{-\gamma_1R_0}+(z+h)e^{-\gamma_1R_1}\right]\Big\}$
$\frac{\text{in}\ \phi}{3}\Big\{[\gamma_1\rho W+\gamma_0\rho(1+F)]e^{-\gamma_0\rho}e^{-\gamma_1(z+h)}$ $\frac{h)e^{-\gamma_1R_1}}{\rho^2}\Big[(12+12\gamma_1\rho+4\gamma_1^2\rho^2)-\frac{(z+h)^2}{\rho^2}(15+15\gamma_1\rho$ $\gamma_1^3\rho^3)\Big]-\frac{(1+\gamma_1\rho)}{2}\Big[\gamma_1(z-h)e^{-\gamma_1R_0}+\gamma_1(z+h)e^{-\gamma_1R_1}\Big]\Big]\Big\}$	$\frac{i\omega\mu_0 m\cos\phi}{2\pi\rho^2}\Big[\left(\frac{1}{n^2}\right)(1+\gamma_0\rho F)e^{-\gamma_0\rho}e^{-\gamma_1(z+h)}$ $+\frac{1}{2}(1+\gamma_1\rho)\left(e^{-\gamma_1R_0}-e^{-\gamma_1R_1}\right)\Big]$

2

Table 3. Magnetic-Field Subsurface
$[|n^2| \geq 10, \rho$

Dipole Type	H_ρ	H
VED	0	$\frac{p}{2\pi\rho^2}\left[\left(\frac{1}{n^2}\right)(1 + \gamma_0\rho F)e^{-\gamma_0\rho}e^{-\gamma_1(z+h)}\right.$ $\left.+ \frac{1}{2}(1 + \gamma_1\rho)\left(e^{-\gamma_1 R_0} - e^{-\gamma_1 R_1}\right)\right]$
VMD	$\frac{m}{2\pi\gamma_1\rho^4}\left\{\left(\frac{\gamma_1\rho}{2}T + 3\gamma_0\rho + \gamma_0^2\rho^2\right)e^{-\gamma_0\rho}e^{-\gamma_1(z+h)}\right.$ $- \frac{\gamma_1(z+h)}{\gamma_1^2\rho^2}e^{-\gamma_1 R_1}\left[(45 + 45\gamma_1\rho + 18\gamma_1^2\rho^2 + 3\gamma_1^3\rho^3)\right.$ $\left.- \frac{(z+h)^2}{\rho^2}(105 + 105\gamma_1\rho + 45\gamma_1^2\rho^2 + 10\gamma_1^3\rho^3 + \gamma_1^4\rho^4)\right]$ $\left.+ \frac{(3 + 3\gamma_1\rho + \gamma_1^2\rho^2)}{2}\left[\gamma_1(z-h)e^{-\gamma_1 R_0} - \gamma_1(z+h)e^{-\gamma_1 R_1}\right]\right\}$	

*Argument of modified Bessel functions is $\gamma_1\rho/2$.

ld Subsurface-to-Subsurface Propagation Formulas
$[|n^2| \geq 10,\ \rho \geq 3(z + h)]$*

H_ϕ	H_z
$-\gamma_0\rho_e^{-\gamma_1(z+h)}$ ... $- e^{-\gamma_1 R_1}\Big)\Big]$	0
0	$-\dfrac{m}{2\pi(\gamma_1^2 - \gamma_0^2)\rho^5}\Bigg\{(9 + 9\gamma_0\rho + 4\gamma_0^2\rho^2 + \gamma_0^3\rho^3)e^{-\gamma_0\rho}e^{-\gamma_1(z+h)}$ $- e^{-\gamma_1 R_1}\Bigg[(9 + 9\gamma_1\rho + 4\gamma_1^2\rho^2 + \gamma_1^3\rho^3)$ $- \dfrac{(z + h)^2}{\rho^2}(90 + 90\gamma_1\rho + 39\gamma_1^2\rho^2 + 9\gamma_1^3\rho^3 + \gamma_1^4\rho^4)\Bigg]$ $+ \dfrac{(\gamma_1^2 - \gamma_0^2)\rho^2}{2}(1 + \gamma_1\rho + \gamma_1^2\rho^2)\Big(e^{-\gamma_1 R_0} - e^{-\gamma_1 R_1}\Big)\Bigg\}$

L 2

Table 3. (Cont'd) Magnetic-Field Su
[$|n^2| \geq 1$

Dipole Type	H_ρ	
HED	$-\frac{p\sin\phi}{2\pi\gamma_1\rho^3}\Big\{[\gamma_1\rho W + \gamma_0\rho(1+F)]e^{-\gamma_0\rho}e^{-\gamma_1(z+h)}$ $-\frac{\gamma_1(z+h)}{\gamma_1^2\rho^2}e^{-\gamma_1R_1}\Big[(12 + 12\gamma_1\rho + 4\gamma_1^2\rho^2)$ $-\frac{(z+h)^2}{\rho^2}(15 + 15\gamma_1\rho + 6\gamma_1^2\rho^2 + \gamma_1^3\rho^3)\Big]$ $+\frac{(1+\gamma_1\rho)}{2}\Big[\gamma_1(z-h)e^{-\gamma_1R_0} - \gamma_1(z+h)e^{-\gamma_1R_1}\Big]\Big\}$	$\frac{p\cos\phi}{2\pi\gamma_1\rho^3}\Big\{(\gamma_1\rho I_1K_1 + \gamma_0\rho + \gamma_0^2\rho$ $-\frac{\gamma_1(z+h)}{\gamma_1^2\rho^2}(3 + 3\gamma_1\rho + \gamma_1^2\rho^2)$ $-\frac{(1+\gamma_1\rho)}{2}\Big[\gamma_1(z-h)e^{-\gamma_1R_0}$
HMD	$\frac{m\sin\phi}{2\pi\rho^3}\Big\{\Big[2 + \gamma_0\rho(1+F) - \frac{12}{\gamma_1^2\rho^2}\Big]e^{-\gamma_0\rho}e^{-\gamma_1(z+h)}$ $+(1+\gamma_1\rho)e^{-\gamma_1R_0} + \frac{e^{-\gamma_1R_1}}{\gamma_1^2\rho^2}\Big[(12 + 12\gamma_1\rho + \gamma_1^2\rho^2)$ $-\frac{(z+h)^2}{\rho^2}(105 + 105\gamma_1\rho + 45\gamma_1^2\rho^2 + 10\gamma_1^3\rho^3 + \gamma_1^4\rho^4)\Big]$ $-(3 + 3\gamma_1\rho + \gamma_1^2\rho^2)\Big[\frac{(z-h)^2}{2\rho^2}e^{-\gamma_1R_0} - \frac{(z+h)^2}{2\rho^2}e^{-\gamma_1R_1}\Big]\Big\}$	$-\frac{m\cos\phi}{2\pi\rho^3}\Big\{\Big((1 + \gamma_0\rho + \gamma_0^2\rho^2F -$ $+\frac{e^{-\gamma_1R_1}}{\gamma_1^2\rho^2}\Big[(3 + 3\gamma_1\rho + \gamma_1^2\rho^2) -$ $+\frac{1}{2}(1 + \gamma_1\rho + \gamma_1^2\rho^2)\Big(e^{-\gamma_1R_0} -$

*Argument of modified Bessel functions is $\gamma_1\rho/2$.

ield Subsurface-to-Subsurface Propagation Formulas
$^2| \geq 10,\ \rho \geq 3(z + h)]$*

H_ϕ	H_z
$\rho + \gamma_0^2\rho^2 F)e^{-\gamma_0\rho}e^{-\gamma_1(z+h)}$ $+ \gamma_1^2\rho^2)e^{-\gamma_1 R_1}$ $e^{-\gamma_1 R_0} + \gamma_1(z + h)e^{-\gamma_1 R_1}\Big]\Big\}$	$\dfrac{p \sin \phi}{2\pi(\gamma_1^2 - \gamma_0^2)\rho^4}\Big\{(3 + 3\gamma_0\rho + \gamma_0^2\rho^2)e^{-\gamma_0\rho}e^{-\gamma_1(z+h)}$ $- e^{-\gamma_1 R_1}\Big[(3 + 3\gamma_1\rho + \gamma_1^2\rho^2) - \dfrac{(z + h)^2}{\rho^2}(15 + 15\gamma_1\rho + 6\gamma_1^2\rho^2 + \gamma_1^3\rho^3)\Big]$ $+ \dfrac{(\gamma_1^2 - \gamma_0^2)\rho^2}{2}(1 + \gamma_1\rho)\left(e^{-\gamma_1 R_0} - e^{-\gamma_1 R_1}\right)\Big\}$
$\gamma_0^2\rho^2 F - \dfrac{3}{\gamma_1^2\rho^2}\Big)e^{-\gamma_0\rho}e^{-\gamma_1(z+h)}$ $\gamma_1^2\rho^2) - \dfrac{(z + h)^2}{\rho^2}(15 + 15\gamma_1\rho + 6\gamma_1^2\rho^2 + \gamma_1^3\rho^3)\Big]$ $e^{-\gamma_1 R_0} - e^{-\gamma_1 R_1}\Big)\Big]\Big\}$	$- \dfrac{m \sin \phi}{2\pi\gamma_1\rho^4}\Big\{\Big(\dfrac{\gamma_1\rho}{2}T + 3\gamma_0\rho + \gamma_0^2\rho^2\Big)e^{-\gamma_0\rho}e^{-\gamma_1(z+h)}$ $- \dfrac{\gamma_1(z + h)e^{-\gamma_1 R_1}}{\gamma_1^2\rho^2}\Big[(45 + 45\gamma_1\rho + 18\gamma_1^2\rho^2 + 3\gamma_1^3\rho^3)$ $- \dfrac{(z + h)^2}{\rho^2}(105 + 105\gamma_1\rho + 45\gamma_1^2\rho^2 + 10\gamma_1^3\rho^3 + \gamma_1^4\rho^4)\Big]$ $- \dfrac{(3 + 3\gamma_1\rho + \gamma_1^2\rho^2)}{2}\Big[\gamma_1(z - h)e^{-\gamma_1 R_0} + \gamma_1(z + h)e^{-\gamma_1 R_1}\Big]\Big\}$

2

Table 4. Electric-Field Subsurface-to-Surface Pro

Dipole Type	E_ρ	
VED	$\frac{p}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^2}\left[\left(\frac{\gamma_1}{n^2}\right)(\gamma_1\rho I_1K_1 + \gamma_0\rho F)e^{-\gamma_0\rho}e^{-\gamma_1 h}\right.$ $\left.- \frac{h}{\rho^2}(3 + 3\gamma_1\rho + \gamma_1^2\rho^2)e^{-\gamma_1 D}\right]$	
VMD	0	$- \frac{i\omega\mu_0 m}{2\pi(\gamma_1^2 - \gamma_0^2)\rho}$ $- e^{-\gamma_1 D}[(3 + 3$ $- \frac{h^2}{\rho^2}(15 + 15\gamma_1$
HED	$\frac{p\cos\phi}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho^3}\left\{(1 + \gamma_0\rho + \gamma_0^2\rho^2F)e^{-\gamma_0\rho}e^{-\gamma_1 h}\right.$ $\left.+ e^{-\gamma_1 D}\left[(1 + \gamma_1\rho) - \frac{h^2}{\rho^2}(3 + 3\gamma_1\rho + \gamma_1^2\rho^2)\right]\right\}$	$\frac{p\sin\phi}{2\pi(\sigma_1 + i\omega\epsilon_1)\rho}$ $- e^{-\gamma_1 D}[(1 + \gamma$
HMD	$- \frac{i\omega\mu_0 m\cos\phi}{2\pi\gamma_1\rho^3}\left[(\gamma_1\rho I_1K_1 + \gamma_0\rho + \gamma_0^2\rho^2F)e^{-\gamma_0\rho}e^{-\gamma_1 h}\right.$ $\left.- \frac{\gamma_1 h}{\gamma_1^2\rho^2}(3 + 3\gamma_1\rho + 2\gamma_1^2\rho^2 + \gamma_1^3\rho^3)e^{-\gamma_1 D}\right]$	$- \frac{i\omega\mu_0 m\sin\phi}{2\pi\gamma_1\rho^3}$ $- \frac{\gamma_1 h e^{-\gamma_1 D}}{\gamma_1^2\rho^2}[(12$ $- \frac{h^2}{\rho^2}(15 + 15\gamma_1$

*Argument of modified Bessel functions is $\gamma_1\rho/2$.

-to-Surface Propagation Formulas $[|n^2| \geq 10,\ \rho \geq 3h,\ D = (\rho^2 + h2)^{1/2}]$*

E_ϕ	E_z
0	$-\frac{p}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^3}(1 + \gamma_0\rho + \gamma_0^2\rho^2 F)e^{-\gamma_0\rho}e^{-\gamma_1 h}$
$-\frac{i\omega\mu_0 m}{2\pi(\gamma_1^2 - \gamma_0^2)\rho^4}\Big\{(3 + 3\gamma_0\rho + \gamma_0^2\rho^2)e^{-\gamma_0\rho}e^{-\gamma_1 h} - e^{-\gamma_1 D}\Big[(3 + 3\gamma_1\rho + \gamma_1^2\rho^2) - \frac{h^2}{\rho^2}(15 + 15\gamma_1\rho + 6\gamma_1^2\rho^2 + \gamma_1^3\rho^3)\Big]\Big\}$	0
$\frac{p \sin\phi}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^3}\Big\{[2 + \gamma_0\rho(1 + F)]e^{-\gamma_0\rho}e^{-\gamma_1 h} - e^{-\gamma_1 D}\Big[(1 + \gamma_1\rho) - \frac{h^2}{\rho^2}(3 + 3\gamma_1\rho + \gamma_1^2\rho^2)\Big]\Big\}$	$-\frac{\gamma_1 p \cos\phi}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^2}(\gamma_1\rho I_1 K_1 + \gamma_0\rho F)e^{-\gamma_0\rho}e^{-\gamma_1 h}$
$-\frac{i\omega\mu_0 m \sin\phi}{2\pi\gamma_1\rho^3}\Big\{[\gamma_1\rho W + \gamma_0\rho(1 + F)]e^{-\gamma_0\rho}e^{-\gamma_1 h} - \frac{\gamma_1 h e^{-\gamma_1 D}}{\gamma_1^2\rho^2}\Big[(12 + 12\gamma_1\rho + 4\gamma_1^2\rho^2) - \frac{h^2}{\rho^2}(15 + 15\gamma_1\rho + 6\gamma_1^2\rho^2 + \gamma_1^3\rho^3)\Big]\Big\}$	$\frac{i\omega\mu_0 m \cos\phi}{2\pi\rho^2}(1 + \gamma_0\rho F)e^{-\gamma_0\rho}e^{-\gamma_1 h}$

Table 5. Magnetic-Field Subsurface-to-Su

Dipole Type	H_ρ	
VED	0	$\frac{p}{2\pi n^2\rho^2}(1 +$
VMD	$\frac{m}{2\pi\gamma_1\rho^4}\left\{\left(\frac{\gamma_1\rho}{2}T + 3\gamma_0\rho + \gamma_0^2\rho^2\right)e^{-\gamma_0\rho}e^{-\gamma_1 h}\right.$ $- \frac{\gamma_1 h}{\gamma_1^2\rho^2}\left[(45 + 45\gamma_1\rho + 21\gamma_1^2\rho^2 + 6\gamma_1^3\rho^3 + \gamma_1^4\rho^4)\right.$ $\left.\left. - \frac{h^2}{\rho^2}(105 + 105\gamma_1\rho + 45\gamma_1^2\rho^2 + 10\gamma_1^3\rho^3 + \gamma_1^4\rho^4)\right]e^{-\gamma_1 D}\right\}$	
HED	$- \frac{p \sin\phi}{2\pi\gamma_1\rho^3}\left\{[\gamma_1\rho W + \gamma_0\rho(1 + F)]e^{-\gamma_0\rho}e^{-\gamma_1 h}\right.$ $\left. - \frac{\gamma_1 h}{\gamma_1^2\rho^2}(12 + 12\gamma_1\rho + 5\gamma_1^2\rho^2 + \gamma_1^3\rho^3)e^{-\gamma_1 D}\right\}$	$\frac{p\cos\phi}{2\pi\gamma_1\rho^3}\left\{\left[(\gamma_1\right.\right.$ $- \frac{\gamma_1 h}{\gamma_1^2\rho^2}(3 +$
HMD	$\frac{m \sin\phi}{2\pi\rho^3}\left\{\left[2 + \gamma_0\rho(1 + F) - \frac{12}{\gamma_1^2\rho^2}\right]e^{-\gamma_0\rho}e^{-\gamma_1 h}\right.$ $+ \frac{e^{-\gamma_1 D}}{\gamma_1^2\rho^2}\left[(12 + 12\gamma_1\rho + 5\gamma_1^2\rho^2 + \gamma_1^3\rho^3)\right.$ $\left.\left. - \frac{h^2}{\rho^2}(105 + 105\gamma_1\rho + 45\gamma_1^2\rho^2 + 10\gamma_1^3\rho^3 + \gamma_1^4\rho^4)\right]\right\}$	$- \frac{m\cos\phi}{2\pi\rho^3}\left\{\left(\right.\right.$ $+ \frac{e^{-\gamma_1 D}}{\gamma_1^2\rho^2}\left[\right.$ $- \frac{h^2}{\rho^2}(15 + 1$

*Argument of modified Bessel functions is $\gamma_1\rho/2$.

...to-Surface Propagation Formulas $[|n^2| \geq 10,\ \rho \geq 3h,\ D = (\rho^2 + h^2)^{1/2}]$*

H_ϕ	H_z
$\frac{\ }{\rho^2}(1 + \gamma_0\rho F)e^{-\gamma_0\rho}e^{-\gamma_1 h}$	0
0	$-\frac{m}{2\pi(\gamma_1^2 - \gamma_0^2)\rho^5}\Big\{(9 + 9\gamma_0\rho + 4\gamma_0^2\rho^2 + \gamma_0^3\rho^3)e^{-\gamma_0\rho}e^{-\gamma_1 h} - e^{-\gamma_1 D}\Big[(9 + 9\gamma_1\rho + 4\gamma_1^2\rho^2 + \gamma_1^3\rho^3) - \frac{h^2}{\rho^2}(90 + 90\gamma_1\rho + 39\gamma_1^2\rho^2 + 9\gamma_1^3\rho^3 + \gamma_1^4\rho^4)\Big]\Big\}$
$\frac{\ s\ \phi}{\rho^3}\Big[(\gamma_1\rho I_1K_1 + \gamma_0\rho + \gamma_0^2\rho^2F)e^{-\gamma_0\rho}e^{-\gamma_1 h}$ $\frac{\ _1h}{\rho^2}(3 + 3\gamma_1\rho + \gamma_1^2\rho^2)e^{-\gamma_1 D}\Big]$	$\frac{p\sin\phi}{2\pi(\gamma_1^2 - \gamma_0^2)\rho^4}\Big\{(3 + 3\gamma_0\rho + \gamma_0^2\rho^2)e^{-\gamma_0\rho}e^{-\gamma_1 h} - e^{-\gamma_1 D}\Big[(3 + 3\gamma_1\rho + \gamma_1^2\rho^2) - \frac{h^2}{\rho^2}(15 + 15\gamma_1\rho + \gamma_1^2\rho^2 + \gamma_1^3\rho^3)\Big]\Big\}$
$\frac{\cos\phi}{2\pi\rho^3}\Big\{\Big(1 + \gamma_0\rho + \gamma_0^2\rho^2F - \frac{3}{\gamma_1^2\rho^2}\Big)e^{-\gamma_0\rho}e^{-\gamma_1 h}$ $\frac{\gamma_1 D}{\rho^2}\Big[(3 + 3\gamma_1\rho + \gamma_1^2\rho^2)$ $(15 + 15\gamma_1\rho + 6\gamma_1^2\rho^2 + \gamma_1^3\rho^3)\Big]\Big\}$	$-\frac{m}{2\pi\gamma_1\rho^4}\Big\{\Big(\frac{\gamma_1\rho}{2}T + 3\gamma_0\rho + \gamma_0^2\rho^2\Big)e^{-\gamma_0\rho}e^{-\gamma_1 h} - \frac{\gamma_1 h e^{-\gamma_1 D}}{\gamma_1^2\rho^2}\Big[(45 + 45\gamma_1\rho + 18\gamma_1^2\rho^2 + 3\gamma_1^3\rho^3) - \frac{h^2}{\rho^2}(105 + 105\gamma_1\rho + 45\gamma_1^2\rho^2 + 10\gamma_1^3\rho^3 + \gamma_1^4\rho^4)\Big]\Big\}$

2

Table 6. Electric-Field Surface-to-Subsurf

Dipole Type	E_ρ	
VED	$\frac{\gamma_1 p}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^2}(\gamma_1\rho I_1 K_1 + \gamma_0\rho F)e^{-\gamma_0\rho}e^{-\gamma_1 z}$	
VMD	0	$-\frac{i\omega\mu_0 m}{2\pi(\gamma_1^2 - \gamma_0^2}$ $- e^{-\gamma_1 R}\Big[(3 +$ $-\frac{z^2}{\rho^2}(15 + 15$
HED	$\frac{p\cos\phi}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^3}\Big\{(1 + \gamma_0\rho + \gamma_0^2\rho^2 F)e^{-\gamma_0\rho}e^{-\gamma_1 z} + e^{-\gamma_1 R}\Big[(1 + \gamma_1\rho) - \frac{z^2}{\rho^2}(3 + 3\gamma_1\rho + \gamma_1^2\rho^2)\Big]\Big\}$	$\frac{p\sin\phi}{2\pi(\sigma_1 + i\omega\varepsilon_1}$ $- e^{-\gamma_1 R}\Big[(1 +$
HMD	$-\frac{i\omega\mu_0 m\cos\phi}{2\pi\gamma_1\rho^3}\Big[(\gamma_1\rho I_1 K_1 + \gamma_0\rho + \gamma_0^2\rho^2 F)e^{-\gamma_0\rho}e^{-\gamma_1 z} - \frac{\gamma_1 z}{\gamma_1^2\rho^2}(3 + 3\gamma_1\rho + \gamma_1^2\rho^2)e^{-\gamma_1 R}\Big]$	$-\frac{i\omega\mu_0 m\sin\phi}{2\pi\gamma_1\rho^3}$ $-\frac{\gamma_1 z}{\gamma_1^2\rho^2}(12 + 1$

*Argument of modified Bessel functions is $\gamma_1\rho/2$.

-to-Subsurface Propagation Formulas [$|n^2| \geq 10$, $\rho \geq 3z$, $R = (\rho^2 + z^2)^{1/2}$]*

E_ϕ	E_z
0	$-\dfrac{p}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^3}(1 + \gamma_0\rho + \gamma_0^2\rho^2 F)e^{-\gamma_0\rho}e^{-\gamma_1 z}$
$\dfrac{i\omega\mu_0 m}{2\pi(\gamma_1^2 - \gamma_0^2)\rho^4}\Bigg\{(3 + 3\gamma_0\rho + \gamma_0^2\rho^2)e^{-\gamma_0\rho}e^{-\gamma_1 z}$ $e^{-\gamma_1 R}\Bigg[(3 + 3\gamma_1\rho + \gamma_1^2\rho^2)$ $\dfrac{z^2}{\rho^2}(15 + 15\gamma_1\rho + 6\gamma_1^2\rho^2 + \gamma_1^3\rho^3)\Bigg]\Bigg\}$	0
$\dfrac{p \sin\phi}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^3}\Bigg\{[2 + \gamma_0\rho(1 + F)]e^{-\gamma_0\rho}e^{-\gamma_1 z}$ $- e^{-\gamma_1 R}\Bigg[(1 + \gamma_1\rho) - \dfrac{z^2}{\rho^2}(3 + 3\gamma_1\rho + \gamma_1^2\rho^2)\Bigg]\Bigg\}$	$-\dfrac{p \cos\phi}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^2}\Bigg[\left(\dfrac{\gamma_1}{n^2}\right)(\gamma_1\rho I_1K_1 + \gamma_0\rho F)e^{-\gamma_0\rho}e^{-\gamma_1 z}$ $- \dfrac{z}{\rho^2}(3 + 3\gamma_1\rho + \gamma_1^2\rho^2)e^{-\gamma_1 R}\Bigg]$
$\dfrac{i\omega\mu_0 m \sin\phi}{2\pi\gamma_1\rho^3}\Bigg[[\gamma_1\rho W + \gamma_0\rho(1 + F)]e^{-\gamma_0\rho}e^{-\gamma_1 z}$ $\dfrac{\gamma_1 z}{\gamma_1^2\rho^2}(12 + 12\gamma_1\rho + 5\gamma_1^2\rho^2 + \gamma_1^3\rho^3)e^{-\gamma_1 R}\Bigg]$	$\dfrac{i\omega\mu_0 m \cos\phi}{2\pi n^2\rho^2}(1 + \gamma_0\rho F)e^{-\gamma_0\rho}e^{-\gamma_1 z}$

Table 7. Magnetic-Field Surface-to-Subsurfac

Dipole Type	H_ρ	
VED	0	$\frac{p}{2\pi\rho^2}(1 + \gamma_0\rho F$
VMD	$\frac{m}{2\pi\gamma_1\rho^4}\left\{\left(\frac{\gamma_1\rho}{2}T + 3\gamma_0\rho + \gamma_0^2\rho^2\right)e^{-\gamma_0\rho}e^{-\gamma_1 z}\right.$ $- \frac{\gamma_1 z}{\gamma_1^2\rho^2}\left[(45 + 45\gamma_1\rho + 18\gamma_1^2\rho^2 + 3\gamma_1^3\rho^3)\right.$ $\left.\left.- \frac{z^2}{\rho^2}(105 + 105\gamma_1\rho + 45\gamma_1^2\rho^2 + 10\gamma_1^3\rho^3 + \gamma_1^4\rho^4)\right]e^{-\gamma_1 R}\right\}$	
HED	$- \frac{p \sin\phi}{2\pi\gamma_1\rho^3}\left\{[\gamma_1\rho W + \gamma_0\rho(1 + F)]e^{-\gamma_0\rho}e^{-\gamma_1 z}\right.$ $- \frac{\gamma_1 z e^{-\gamma_1 R}}{\gamma_1^2\rho^2}\left[(12 + 12\gamma_1\rho + 4\gamma_1^2\rho^2)\right.$ $\left.\left.- \frac{z^2}{\rho^2}(15 + 15\gamma_1\rho + 6\gamma_1^2\rho^2 + \gamma_1^3\rho^3)\right]\right\}$	$\frac{p\cos\phi}{2\pi\gamma_1\rho^3}\left[(\gamma_1\rho I\right.$ $- \frac{\gamma_1 z}{\gamma_1^2\rho^2}(3 + 3\gamma$
HMD	$\frac{m \sin\phi}{2\pi\rho^3}\left\{\left[2 + \gamma_0\rho(1 + F) - \frac{12}{\gamma_1^2\rho^2}\right]e^{-\gamma_0\rho}e^{-\gamma_1 z}\right.$ $+ \frac{e^{-\gamma_1 R}}{\gamma_1^2\rho^2}\left[(12 + 12\gamma_1\rho + 5\gamma_1^2\rho^2 + \gamma_1^3\rho^3)\right.$ $\left.\left.- \frac{z^2}{\rho^2}(105 + 105\gamma_1\rho + 45\gamma_1^2\rho^2 + 10\gamma_1^3\rho^3 + \gamma_1^4\rho^4\right]\right\}$	$- \frac{m\cos\phi}{2\pi\rho^3}\left\{\left(1 +\right.\right.$ $+ \frac{e^{-\gamma_1 R}}{\gamma_1^2\rho^2}\left[(3 + 3\right.$ $- \frac{z^2}{\rho^2}(15 + 15\gamma$

*Argument of modifi^d Bessel functions is $\gamma_1\rho/2$.

o-Subsurface Propagation Formulas $[|n^2| \geq 10,\ \rho \geq 3z,\ R = (\rho^2 + z^2)^{1/2}]$*

H_ϕ	H_z
$\frac{}{\rho^2}(1 + \gamma_0\rho F)e^{-\gamma_0\rho}e^{-\gamma_1 z}$	0
0	$-\frac{m}{2\pi(\gamma_1^2 - \gamma_0^2)\rho^5}\Big\{(9 + 9\gamma_0\rho + 4\gamma_0^2\rho^2 + \gamma_0^3\rho^3)e^{-\gamma_0\rho}e^{-\gamma_1 z} - e^{-\gamma_1 R}\Big[(9 + 9\gamma_1\rho + 4\gamma_1^2\rho^2 + \gamma_1^3\rho^3) - \frac{z^2}{\rho^2}(90 + 90\gamma_1\rho + 39\gamma_1^2\rho^2 + 9\gamma_1^3\rho^3 + \gamma_1^4\rho^4)\Big]\Big\}$
$\frac{\cos\phi}{\gamma_1\rho^3}\Big[(\gamma_1\rho I_1K_1 + \gamma_0\rho + \gamma_0^2\rho^2F)e^{-\gamma_0\rho}e^{-\gamma_1 z}$ $\frac{\gamma_1 z}{\gamma_1^2\rho^2}(3 + 3\gamma_1\rho + 2\gamma_1^2\rho^2 + \gamma_1^3\rho^3)e^{-\gamma_1 R}\Big]$	$\frac{p\sin\phi}{2\pi(\gamma_1^2 - \gamma_0^2)\rho^4}\Big\{(3 + 3\gamma_0\rho + \gamma_0^2\rho^2)e^{-\gamma_0\rho}e^{-\gamma_1 z} - e^{-\gamma_1 R}\Big[(3 + 3\gamma_1\rho + \gamma_1^2\rho^2) - \frac{z^2}{\rho^2}(15 + 15\gamma_1\rho + 6\gamma_1^2\rho^2 + \gamma_1^3\rho^3)\Big]\Big\}$
$\frac{m\cos\phi}{2\pi\rho^3}\Big\{\Big(1 + \gamma_0\rho + \gamma_0^2\rho^2F - \frac{3}{\gamma_1^2\rho^2}\Big)e^{-\gamma_0\rho}e^{-\gamma_1 z}$ $\frac{e^{-\gamma_1 R}}{\gamma_1^2\rho^2}\Big[(3 + 3\gamma_1\rho + \gamma_1^2\rho^2)$. $\frac{z^2}{\rho^2}(15 + 15\gamma_1\rho + 6\gamma_1^2\rho^2 + \gamma_1^3\rho^3)\Big]\Big\}$	$-\frac{m}{2\pi\gamma_1\rho^4}\Big\{\Big(\frac{\gamma_1\rho}{2}T + 3\gamma_0\rho + \gamma_0^2\rho^2\Big)e^{-\gamma_0\rho}e^{-\gamma_1 z} - \frac{\gamma_1 z e^{-\gamma_1 R}}{\gamma_1^2\rho^2}\Big[(45 + 45\gamma_1\rho + 21\gamma_1^2\rho^2 + 6\gamma_1^3\rho^3 + \gamma_1^4\rho^4) - \frac{z^2}{\rho^2}(105 + 105\gamma_1\rho + 45\gamma_1^2\rho^2 + 10\gamma_1^3\rho^3 + \gamma_1^4\rho^4)\Big]\Big\}$

1 2

Table 8. Electric-Field Surface-to-Surface Propagati

Dipole Type	E_ρ	E_ϕ
VED	$\frac{\gamma_1 p}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^2}(\gamma_1\rho I_1 K_1 + \gamma_0\rho F)e^{-\gamma_0\rho}$	0
VMD	0	$\equiv -\frac{i\omega\mu_0 m}{2\pi(\gamma_1^2 - \gamma_0^2)\rho^4}\Big[(3 + 3\gamma_0\rho +$ $- (3 + 3\gamma_1\rho + \gamma_1^2\rho^2)e^{-\gamma_1\rho}\Big]$
HED	$\frac{p \cos\phi}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^3}\Big[(1 + \gamma_0\rho + \gamma_0^2\rho^2 F)e^{-\gamma_0\rho}$ $+ (1 + \gamma_1\rho)e^{-\gamma_1\rho}\Big]$	$\frac{p \sin\phi}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^3}\Big\{[2 + \gamma_0\rho(1 + F$ $- (1 + \gamma_1\rho)e^{-\gamma_1\rho}\Big\}$
HMD	$-\frac{i\omega\mu_0 m \cos\phi}{2\pi\gamma_1\rho^3}(\gamma_1\rho I_1 K_1 + \gamma_0\rho + \gamma_0^2\rho^2 F)$ $\times e^{-\gamma_0\rho}$	$-\frac{i\omega\mu_0 m \sin\phi}{2\pi\gamma_1\rho^3}[\gamma_1\rho W + \gamma_0\rho(1 + F)$

*Argument of modified Bessel functions is $\gamma_1\rho/2$.

ectric-Field Surface-to-Surface Propagation Formulas ($|n^2| \geq 10$)*

	E_ϕ	E_z
$e^{-\gamma_0\rho}$	0	$-\frac{p}{2\pi i\omega\varepsilon_0\rho^3}(1 + \gamma_0\rho + \gamma_0^2\rho^2 F)e^{-\gamma_0\rho}$
	$= -\frac{i\omega\mu_0 m}{2\pi(\gamma_1^2 - \gamma_0^2)\rho^4}\Big[(3 + 3\gamma_0\rho + \gamma_0^2\rho^2)e^{-\gamma_0\rho} - (3 + 3\gamma_1\rho + \gamma_1^2\rho^2)e^{-\gamma_1\rho}\Big]$	0
$F)e^{-\gamma_0\rho}$	$\frac{p \sin\phi}{2\pi(\sigma_1 + i\omega\varepsilon_1)\rho^3}\Big\{[2 + \gamma_0\rho(1 + F)]e^{-\gamma_0\rho} - (1 + \gamma_1\rho)e^{-\gamma_1\rho}\Big\}$	$-\frac{i\omega\mu_0 p \cos\phi}{2\pi\gamma_1\rho^2}(\gamma_1\rho I_1 K_1 + \gamma_0\rho F)e^{-\gamma_0\rho}$
${}_0^2\rho^2 F)$	$-\frac{i\omega\mu_0 m \sin\phi}{2\pi\gamma_1\rho^3}[\gamma_1\rho W + \gamma_0\rho(1 + F)]e^{-\gamma_0\rho}$	$\frac{i\omega\mu_0 m \cos\phi}{2\pi\rho^2}(1 + \gamma_0\rho F)e^{-\gamma_0\rho}$

ons is $\gamma_1\rho/2$.

2

Table 9. Magnetic-Field Surface-

Dipole Type	H_ρ	
VED	0	$\frac{p}{2\pi\rho^2}(1 + \gamma_0\rho F)$
VMD	$\frac{m}{2\pi\gamma_1\rho^4}\left(\frac{\gamma_1\rho}{2}T + 3\gamma_0\rho + \gamma_0^2\rho^2\right)e^{-\gamma_0\rho}$	
HED	$-\frac{p \sin\phi}{2\pi\gamma_1\rho^3}[\gamma_1\rho W + \gamma_0\rho(1 + F)]e^{-\gamma_0\rho}$	$\frac{p \cos\phi}{2\pi\gamma_1\rho^3}(\gamma_1\rho I_1 K$
HMD	$\frac{m \sin\phi}{2\pi\rho^3}\left\{\left[2 + \gamma_0\rho(1 + F) - \frac{12}{\gamma_1^2\rho^2}\right]e^{-\gamma_0\rho} + (12 + 12\gamma_1\rho + 5\gamma_1^2\rho^2 + \gamma_1^3\rho^3)\frac{e^{-\gamma_1\rho}}{\gamma_1^2\rho^2}\right\}$	$-\frac{m \cos\phi}{2\pi\rho^3}\left[\left(1 +\right.\right.$ $+ (3 + 3\gamma_1\rho + \gamma$

*Argument of modified Bessel functions is $\gamma_1\rho/2$.

Field Surface-to-Surface Propagation Formulas ($|n^2| \geq 10$)*

H_ϕ	H_z
$\frac{p}{2\pi\rho^2}(1 + \gamma_0\rho F)e^{-\gamma_0\rho}$	0
0	$\equiv -\frac{m}{2\pi(\gamma_1^2 - \gamma_0^2)\rho^5}\Big[(9 + 9\gamma_0\rho + 4\gamma_0^2\rho^2 + \gamma_0^3\rho^3)e^{-\gamma_0\rho} - (9 + 9\gamma_1\rho + 4\gamma_1^2\rho^2 + \gamma_1^3\rho^3)e^{-\gamma_1\rho}\Big]$
$\frac{p\cos\phi}{2\pi\gamma_1\rho^3}(\gamma_1\rho I_1 K_1 + \gamma_0\rho + \gamma_0^2\rho^2 F)e^{-\gamma_0\rho}$	$\equiv \frac{p\sin\phi}{2\pi(\gamma_1^2 - \gamma_0^2)\rho^4}\Big[(3 + 3\gamma_0\rho + \gamma_0^2\rho^2)e^{-\gamma_0\rho} - (3 + 3\gamma_1\rho + \gamma_1^2\rho^2)e^{-\gamma_1\rho}\Big]$
$-\frac{m\cos\phi}{2\pi\rho^3}\left[\left(1 + \gamma_0\rho + \gamma_0^2\rho^2 F - \frac{3}{\gamma_1^2\rho^2}\right)e^{-\gamma_0\rho} + (3 + 3\gamma_1\rho + \gamma_1^2\rho^2)\frac{e^{-\gamma_1\rho}}{\gamma_1^2\rho^2}\right]$	$-\frac{m\sin\phi}{2\pi\gamma_1\rho^4}\left(\frac{\gamma_1\rho}{2}T + 3\gamma_0\rho + \gamma_0^2\rho^2\right)e^{-\gamma_0\rho}$

Table 10. Range Where $f(\rho, z + h) = e^{-\gamma_1(z+h)} f(\rho, 0)$

Field-Strength Components			c_1	$\left\lvert(\gamma_1 \rho)\left(\frac{\rho}{z + h}\right)\right\rvert$
HED and HMD	VED	VMD		
E_ρ, E_z, H_ϕ	E_ρ, H_ϕ	--	3	≥ 12
E_ϕ, H_ρ	--	--	6	≥ 24
--	E_z	--	9	≥ 36
H_z	--	E_ϕ, H_ρ	15	≥ 60
--	--	H_z	25	≥ 100

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Appendix

DIRECT AND MODIFIED MIRROR-IMAGE CONTRIBUTION TO EACH DIPOLE FIELD-STRENGTH COMPONENT ($|n^2| >> 1$)

$$E_\rho^{HE} \sim \frac{p\cos\phi}{4\pi(\sigma_1 + i\omega\varepsilon_1)}\left\{\left[(3\cos^2\psi_0 - 1)(1 + \gamma_1 R_0) - \gamma_1^2 R_0^2 \sin^2\psi_0\right]\frac{e^{-\gamma_1 R_0}}{R_0^3} - \left[(3 + 3\gamma_1 R_1 + \gamma_1^2 R_1^2)\sin^2\psi_1\right]\frac{e^{-\gamma_1 R_1}}{R_1^3}\right\}, \tag{A-1}$$

$$E_\phi^{HE} \sim \frac{p\sin\phi}{4\pi(\sigma_1 + i\omega\varepsilon_1)}\left[(1 + \gamma_1 R_0 + \gamma_1^2 R_0^2)\frac{e^{-\gamma_1 R_0}}{R_0^3} - (1 - 2\sin^2\psi_1)(3 + 3\gamma_1 R_1 + \gamma_1^2 R_1^2)\frac{e^{-\gamma_1 R_1}}{R_1^3}\right], \tag{A-2}$$

$$E_z^{HE} \sim \frac{p\cos\phi}{4\pi(\sigma_1 + i\omega\varepsilon_1)}\left[(3 + 3\gamma_1 R_0 + \gamma_1^2 R_0^2)\sin\psi_0\cos\psi_0\,\frac{e^{-\gamma_1 R_0}}{R_0^3} + (3 + 3\gamma_1 R_1 + \gamma_1^2 R_1^2)\sin\psi_1\cos\psi_1\,\frac{e^{-\gamma_1 R_1}}{R_1^3}\right], \tag{A-3}$$

$$H_\rho^{HE} \sim -\frac{p\sin\phi}{4\pi}\left\{(1 + \gamma_1 R_0)\sin\psi_0\,\frac{e^{-\gamma_1 R_0}}{R_0^2} - (1 + \gamma_1 R_1)\sin\psi_1\,\frac{e^{-\gamma_1 R_1}}{R_1^2} - \frac{2\sin\psi_1 e^{-\gamma_1 R_1}}{(\gamma_1^2 - \gamma_0^2)R_1^4}\left[(12 + 12\gamma_1 R_1 + 4\gamma_1^2 R_1^2) - \sin^2\psi_1(15 + 15\gamma_1 R_1 + 6\gamma_1^2 R_1^2 + \gamma_1^3 R_1^3)\right]\right\}, \tag{A-4}$$

$$H_\phi^{HE} \sim -\frac{p\cos\phi}{4\pi}\left[(1 + \gamma_1 R_0)\sin\psi_0\,\frac{e^{-\gamma_1 R_0}}{R_0^2} + (1 + \gamma_1 R_1)\sin\psi_1\,\frac{e^{-\gamma_1 R_1}}{R_1^2} + \frac{2\sin\psi_1 e^{-\gamma_1 R_1}}{(\gamma_1^2 - \gamma_0^2)R_1^4}(3 + 3\gamma_1 R_1 + \gamma_1^2 R_1^2)\right], \tag{A-5}$$

$$H_z^{HE} \sim \frac{p \sin\phi}{4\pi}\left\{(1 + \gamma_1 R_0)\cos\psi_0 \frac{e^{-\gamma_1 R_0}}{R_0^2} - (1 + \gamma_1 R_1)\cos\psi_1 \frac{e^{-\gamma_1 R_1}}{R_1^2}\right.$$

$$- \frac{2\cos\psi_1 e^{-\gamma_1 R_1}}{(\gamma_1^2 - \gamma_0^2)R_1^4}\left[(3 + 3\gamma_1 R_1 + \gamma_1^2 R_1^2)\right. \tag{A-6}$$

$$\left.\left. - \sin^2\psi_1(15 + 15\gamma_1 R_1 + 6\gamma_1^2 R_1^2 + \gamma_1^3 R_1^3)\right]\right\} ,$$

$$E_\rho^{HM} \sim -\frac{i\omega\mu_0 m \cos\phi}{4\pi}\left[(1 + \gamma_1 R_0)\sin\psi_0 \frac{e^{-\gamma_1 R_0}}{R_0^2} - (1 + \gamma_1 R_1)\sin\psi_1 \frac{e^{-\gamma_1 R_1}}{R_1^2}\right. \tag{A-7}$$

$$\left. - \frac{2\sin\psi_1 e^{-\gamma_1 R_1}}{(\gamma_1^2 - \gamma_0^2)R_1^4}(3 + 3\gamma_1 R_1 + \gamma_1^2 R_1^2)\right] ,$$

$$E_\phi^{HM} \sim \frac{i\omega\mu_0 m \sin\phi}{4\pi}\left\{(1 + \gamma_1 R_0)\sin\psi_0 \frac{e^{-\gamma_1 R_0}}{R_0^2} + (1 + \gamma_1 R_1)\sin\psi_1 \frac{e^{-\gamma_1 R_1}}{R_1^2}\right.$$

$$+ \frac{2\sin\psi_1 e^{-\gamma_1 R_1}}{(\gamma_1^2 - \gamma_0^2)R_1^4}\left[(12 + 12\gamma_1 R_1 + 4\gamma_1^2 R_1^2)\right. \tag{A-8}$$

$$\left.\left. - \sin^2\psi_1(15 + 15\gamma_1 R_1 + 6\gamma_1^2 R_1^2 + \gamma_1^3 R_1^3)\right]\right\} ,$$

$$E_z^{HM} \sim \frac{i\omega\mu_0 m \cos\phi}{4\pi}\left[(1 + \gamma_1 R_0)\cos\psi_0 \frac{e^{-\gamma_1 R_0}}{R_0^2} - (1 + \gamma_1 R_1)\cos\psi_1 \frac{e^{-\gamma_1 R_1}}{R_1^2}\right] , \tag{A-9}$$

$$H_\rho^{HM} \sim \frac{m \sin\phi}{4\pi}\left\{\left[(2 - 3\sin^2\psi_0)(1 + \gamma_1 R_0) - \gamma_1^2 R_0^2 \sin^2\psi_0\right]\frac{e^{-\gamma_1 R_0}}{R_0^3}\right.$$

$$+ (3 + 3\gamma_1 R_1 + \gamma_1^2 R_1^2)\sin^2\psi_1 \frac{e^{-\gamma_1 R_1}}{R_1^3} + \frac{2e^{-\gamma_1 R_1}}{(\gamma_1^2 - \gamma_0^2)R_1^5} \tag{A-10}$$

$$\times \left[(12 + 12\gamma_1 R_1 + 4\gamma_1^2 R_1^2) - \sin^2\psi_1\cos^2\psi_1(105 + 105\gamma_1 R_1\right.$$

$$\left.\left. + 45\gamma_1^2 R_1^2 + 10\gamma_1^3 R_1^3 + \gamma_1^4 R_1^4)\right]\right\} ,$$

$$H_\phi^{HM} \sim -\frac{m\cos\phi}{4\pi}\left\{(1 + \gamma_1 R_0 + \gamma_1^2 R_0^2)\frac{e^{-\gamma_1 R_0}}{R_0^3} - (1 + \gamma_1 R_1 + \gamma_1^2 R_1^2)\frac{e^{-\gamma_1 R_1}}{R_1^3}\right.$$

$$+ \frac{2e^{-\gamma_1 R_1}}{(\gamma_1^2 - \gamma_0^2)R_1^5}\Big[(3 + 3\gamma_1 R_1 + \gamma_1^2 R_1^2) \tag{A-11}$$

$$\left. - \sin^2\psi_1(15 + 15\gamma_1 R_1 + 6\gamma_1^2 R_1^2 + \gamma_1^3 R_1^3)\Big]\right\} ,$$

$$H_z^{HM} \sim \frac{m\sin\phi}{4\pi}\left\{(3 + 3\gamma_1 R_0 + \gamma_1^2 R_0^2)\sin\psi_0\cos\psi_0 \ \frac{e^{-\gamma_1 R_0}}{R_0^3}\right.$$

$$+ (3 + 3\gamma_1 R_1 + \gamma_1^2 R_1^2)\sin\psi_1\cos\psi_1 \ \frac{e^{-\gamma_1 R_1}}{R_1^3} \ . \tag{A-12}$$

$$+ \frac{2\sin\psi_1\cos\psi_1 e^{-\gamma_1 R_1}}{(\gamma_1^2 - \gamma_0^2)R_1^5}\Big[(45 + 45\gamma_1 R_1 + 18\gamma_1^2 R^2 + \text{[illegible]}$$

$$\left. - \sin^2\psi_1(105 + 105\gamma_1 R_1 + 45\gamma_1^2 R_1^2 + 10\gamma_1^3 R_1^3 + \gamma_1^4 R_1^4)\Big]\right\} ,$$

$$E_\rho^{VE} \sim \frac{p}{4\pi(\sigma_1 + i\omega\varepsilon_1)}\Big[(3 + 3\gamma_1 R_0 + \gamma_1^2 R_0^2)\sin\psi_0\cos\psi_0 \ \frac{e^{-\gamma_1 R_0}}{R_0^3} \tag{A-13}$$

$$- (3 + 3\gamma_1 R_1 + \gamma_1^2 R_1^2)\sin\psi_1\cos\psi_1 \ \frac{e^{-\gamma_1 R_1}}{R_1^3}\Big],$$

$$E_z^{VE} \sim -\frac{p}{4\pi(\sigma_1 + i\omega\varepsilon_1)}\left\{\Big[(1 - 3\sin^2\psi_0)(1 + \gamma_1 R_0) + \gamma_1^2 R_0^2\cos^2\psi_0\Big]\frac{e^{-\gamma_1 R_0}}{R_0^3}\right. \tag{A-14}$$

$$\left. - \Big[(1 - \text{[illegible]}\sin^2\psi_1)(1 + \gamma_1 R_1) + \gamma_1^2 R_1^2\cos^2\psi_1\Big]\frac{e^{-\gamma_1 R_1}}{R_1^3}\right\} ,$$

$$H_\phi^{VE} \sim \frac{p}{4\pi}\Big[(1 + \gamma_1 R_0)\cos\psi_0 \ \frac{e^{-\gamma_1 R_0}}{R_0^2} - (1 + \gamma_1 R_1)\cos\psi_1 \ \frac{e^{-\gamma_1 R_1}}{R_1^2}\Big], \tag{A-15}$$

$$E_\phi^{VM} \sim -\frac{i\omega\mu_0 m}{4\pi}\Bigg\{(1+\gamma_1R_0)\cos\psi_0\,\frac{e^{-\gamma_1R_0}}{R_0^2} - (1+\gamma_1R_1)\cos\psi_1\,\frac{e^{-\gamma_1R_1}}{R_1^2}$$

$$-\frac{2\cos\psi_1 e^{-\gamma_1R_1}}{(\gamma_1^2-\gamma_0^2)R_1^4}\Big[(3+3\gamma_1R_1+\gamma_1^2R_1^2) \tag{A-16}$$

$$-\sin^2\psi_1(15+15\gamma_1R_1+6\gamma_1^2R_1^2+\gamma_1^3R_1^3)\Big]\Bigg\}\ ,$$

$$H_\rho^{VM} \sim \frac{m}{4\pi}\Bigg\{(3+3\gamma_1R_0+\gamma_1^2R_0^2)\sin\psi_0\cos\psi_0\,\frac{e^{-\gamma_1R_0}}{R_0^3}$$

$$-(3+3\gamma_1R_1+\gamma_1^2R_1^2)\sin\psi_1\cos\psi_1\,\frac{e^{-\gamma_1R_1}}{R_1^3} - \frac{2\sin\psi_1\cos\psi_1 e^{-\gamma_1R_1}}{(\gamma_1^2-\gamma_0^2)R_1^5}$$

$$\times\Big[(45+45\gamma_1R_1+18\gamma_1^2R_1^2+3\gamma_1^3R_1^3) \tag{A-17}$$

$$-\sin^2\psi_1(105+105\gamma_1R_1+45\gamma_1^2R_1^2+10\gamma_1^3R_1^3+\gamma_1^4R_1^4)\Big]\Bigg\}\ ,$$

$$H_z^{VM} \sim -\frac{m}{4\pi}\Bigg\{\Big[(1-3\sin^2\psi_0)(1+\gamma_1R_0)+\gamma_1^2R_0^2\cos^2\psi_0\Big]\frac{e^{-\gamma_1R_0}}{R_0^3}$$

$$-\Big[(1-3\sin^2\psi_1)(1+\gamma_1R_1)+\gamma_1^2R_1^2\cos^2\psi_1\Big]\frac{e^{-\gamma_1R_1}}{R_1^3}$$

$$-\frac{2e^{-\gamma_1R_1}}{(\gamma_1^2-\gamma_0^2)R_1^5}\Big[(9+9\gamma_1R_1+4\gamma_1^2R_1^2+\gamma_1^3R_1^3) \tag{A-18}$$

$$+\sin^2\psi_1(15+15\gamma_1R_1+6\gamma_1^2R_1^2+\gamma_1^3R_1^3)$$

$$-\sin^2\psi_1\cos^2\psi_1(105+105\gamma_1R_1+45\gamma_1^2R_1^2+10\gamma_1^3R_1^3+\gamma_1^4R_1^4)\Big]\Bigg\}\ ,$$

where

$R_0^2 = \rho^2 + (z-h)^2$,

$\sin\psi_0 = (z-h)/R_0$,

$\cos\psi_0 = \rho/R_0$,

$R_1^2 = \rho^2 + (z+h)^2$,

$\sin\psi_1 = (z+h)/R_1$, and

$\cos\psi_1 = \rho/R_1$.

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